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A study of the fading effect on multi-hop wireless ad hoc networks and its mitigation

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Abstract

Ad hoc networks are wireless, mobile networks that do not have neither fixed infrastructure nor centralized administration. The physical phenomena inherent in wireless medium and especially in wave propagation deteriorate data transmissions quality causing therefore a diminishing of ad hoc networks performance.

On the other hand, particular kind of antennas called adaptive array antennas could enable to combat those phenomena. This thesis proposes to study the ad hoc networks routing protocols by enhancing wireless physical layer with adaptive array antennas.

Keywords: ad hoc networks, adaptive array antenna, fading

Résumé

Les réseaux ad hoc sont des réseaux mobiles sans fils qui ne possèdent pas d'infrastructure fixe ni de système d'administration centralisé. Les phénomènes physiques inhérents aux canaux de communication sans fils et en particulier à la propagation des ondes détériorent la qualité de transmission des données causant par conséquent une diminution des performances de ces réseaux.

D'un autre côté, certains types d'antennes appelés réseaux d'antennes adaptatives pourraient permettre de combattre ces phénomènes. Ce mémoire propose d'étudier les performances des protocoles de routages des réseaux ad hoc en équipant la couche physique de réseaux d'antennes adaptatives.

Mots-cléfs: réseaux ad hoc, antennes adaptatives, fading

Contents

List of Figures

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Chapter 1

Introduction

The term “ad hoc” comes from Latin and literally means “for this” or “for this purpose only”. So, an ad hoc network would be a network used for a specific situation or a dedicated scenario. Actually, an ad hoc network can be generally defined as a wireless temporary multi-hop network where all terminals act sometimes as router, sometimes as a host of the network. The capacity of ad hoc networks to overcome the lack of flexibility of semi static networks induces a growing interest in ad hoc network technologies. Accordingly, the network research community has produced many publications about performance of such networks in terms of various criteria, e.g., throughput, end-to-end delay, length of route or processing and signalling overhead.

To obtain their results, authors used simulations of different higher layer algorithms and technologies especially designed to enhance ad hoc networks performance. Those simulations are very useful but do not comply with reality because they consider most of the time an oversimplified physical layer model. Even if some papers consider a more complex model, they do not try to improve the global performance of ad hoc networks by working on the physical layer. However, that is precisely the specificity of wireless network.

On the other hand, the Electronics community develops adaptive array antenna (AAA) systems which combine multiple antenna elements with a signal-processing capability to adapt their radiation pattern automatically in response to the signal environment. So, AAA are designed to deal with physical layer specificities. Especially for RF transmissions, multipath interference phenomenon is of importance on the quality of received signal (fading). In addition, AAA systems have become recently more attractive due to the lower cost of manufacturing.

This study investigates, as a first technical challenge, the effect of the physical layer design on global performance of an ad hoc network in terms of delay and route length. More precisely, the main objective is to show the benefits resulting from the use of the Adaptive Array Antenna at the receiver in an ad hoc network environment. To reach the project objective, several computer simulations have been set up. The first part of the project aims to highlight the dramatic impact of fading on the received signal quality. The second intends to compare the capacity of adaptive array antennas and isotropic antennas to combat fading. Finally, the last part aims to prove that the global performance of ad hoc networks will be enhanced when using Adaptive Array Antennas.

This report reveals how important the physical layer design is for future realizations of wireless ad hoc networks.

The remainder of this thesis is organized as follows. Chapter 2 gives an overview of concepts and technologies used in this Masters thesis. Especially the AODV routing protocol and the adaptive array antenna will be introduced. In addition, it explains which improvements are expected from the use of Adaptive Array Antennas in an ad hoc network environment. Chapter 3 provides the mathematical formulation of the adaptive array antenna and introduces to simple signal modulation techniques. It may be safely skipped if the reader already has background in this field. Simulations characteristics and methodology used for the implementation are detailed in Chapter 4. Finally, simulation results are presented in Chapter 5.

Chapter 2

Preliminaries

In this chapter, key concepts and technologies used in the project will be introduced. The first section introduces ad hoc networking technologies and describes their specificities. Since the relatively simple and efficient AODV routing protocol has been chosen to build an ad hoc environment, it is detailed too. The second section proposes then an intuitive introduction to the wireless channel specificities and to the multipath interference phenomenon. Moreover, it introduces the AAA technology and vocabulary. The third section clarifies what can be expected to achieve by deploying AAA in an ad hoc environment. It highlights, with a typical scenario, which improvements the utilization of AAA could bring. Finally, two promising commercial applications of ad hoc networks enhanced with AAA are illustrated in the last section.

2.1 Ad hoc networks

An ad hoc network is an autonomous system of mobile nodes equipped with wireless communications components. Depending on the scenario, topology can be made of tens of thousands homogeneous or heterogenous devices (Figure 2.1). Those networks operate without any fixed infrastructure or centralized administration (e.g. access point). Indeed, the routing functionality is incorporated into mobile nodes. A node communicates directly with others nodes within its wireless range and indirectly with all other destinations. In other words, a node relays the information that passes through it, or rather forwards packets to the next hop. In that way, a multi hop network is set up between the nodes.

One of the main challenges of mobile ad hoc networks is to overcome the lack of flexibility of static networks by diminishing the costs related to the deployment of infrastructure and by increasing mobility and inter-operability of heterogeneous systems. Practical applications are various and their number increases day by day. However, despite all the

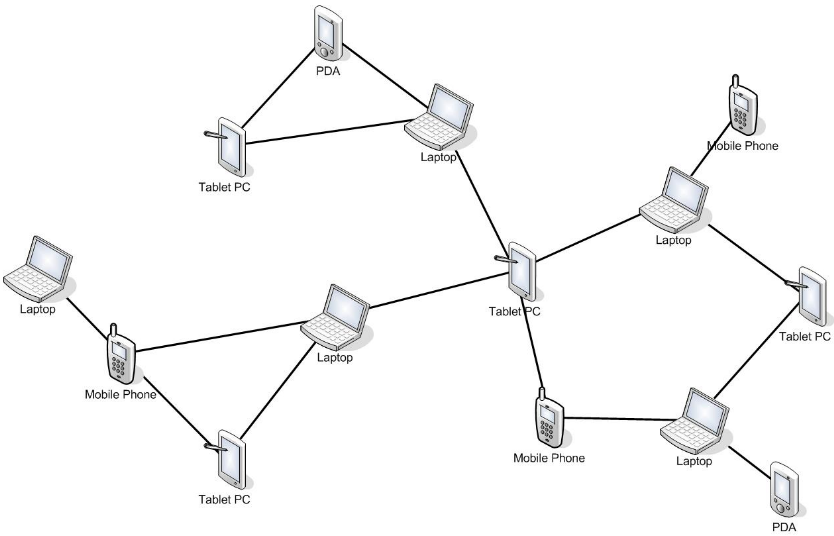

Figure 2.1: An heterogeneous ad hoc network

efforts and the growing interest in mobile ad hoc networks, researchers have to deal with many problems they do not meet in semi-fixed networks. Especially, routing protocols designed for the fixed network are not effective in a dynamic ad hoc network environment. To clarify the reader's idea, this section proposes to enumerate the main constraints and characteristics of ad hoc networks. Afterwards, a taxonomy of the most famous protocols especially designed for ad hoc networks will be presented. In addition, this section focuses on AODV (Ad hoc On-demand Distance Vector) protocol which has been chosen in the present project. The last part of this section approaches some well-known and promising commercial applications.

2.1.1 Ad hoc issues and requirements

Ad hoc network characteristics raise several performance concerns for protocol design which extend beyond those guiding the design of standard routing protocols [S.C99]. Let us study the main ones:

Infrastructureless: The lack of fixed infrastructure, in addition to the wireless nature of the connection, generates new design issues. Typically, the network management has to be distributed across different nodes, which complicates fault detection.

Dynamic topologies: Nodes are free to move arbitrarily. Thus, the network topology may change randomly and rapidly at unpredictable times, and may consist of both bidirectional and unidirectional links.

Bandwidth-constrained and variable capacity links: Because of multiple access, fading, noise and interference conditions, the throughput of wireless communications is often much less than the radio's maximum transmission rate. Indeed, radio interface at each node broadcasts its traffic, causing problems like hidden terminal, exposed terminal and so on. In addition, collisions are inherent to the medium, and there is a higher probability of packet losses due to the transmission errors than in wired systems. For those reasons, wireless links will continue to have a significantly lower capacity than their wired counterparts. A consequence of the relatively low to moderate link capacities is that congestion is typically the norm rather than the exception.

Energy-constrained operation: Some or all the nodes of an ad hoc network are powered by batteries or other exhaustible means. For these nodes, the most important routing design criteria might be energy.

Limited physical security: Mobile wireless networks are generally more vulnerable to physical security threats than fixed wired nets. The use of open and shared broadcast wireless channels means that nodes with inadequate physical protection are prone to security threads. As a benefit, the decentralized nature of network control in ad hoc networks provides additional robustness against the single point of failure vulnerability of the more centralized approaches.

Scalability: Many mobile ad hoc network applications involve large networks with tens of thousands nodes, as , for instance, sensor networks and tactical networks. The evolution towards a larger network of nodes with limited resources is not straightforward and presents many challenges that are still to be solved in areas such as addressing, routing, location management, interoperability and so on.

2.1.2 Taxonomy of Ad hoc routing protocols

The previously detailed challenges in mobile ad hoc networking coupled with the critical importance of routing protocols in establishing communication among mobile nodes, make the routing area one of the most active research fields. Definitely, existing distance-vector and link-state based routing protocols are unable to catch up with ad hoc environments, resulting in slow route convergence, low communication throughput and network congestion.

The ideal ad hoc routing protocol should fulfil the following criteria:

- Be simple and easy to implement
- Have a rapid convergence to route establishment
- Be flexible to changes in topology

- Produce a minimal signaling traffic overhead
- Be power efficient
- Be scalable and reliable
- Be able to support QoS requirements

Over the last few years, numerous and various routing protocols have been proposed and their performance have been assessed. The end of this subsection aims to explore the different kinds of nowadays routing protocols.

A classification inspired from [Fee99] is proposed, focusing on the fundamental design rather than on implementation details. An ad hoc routing protocol can be put together according to several criteria:

Communication model: Wireless routing protocols consider a communication either multi-channel or single channel. A multi-channel protocol can be designed by using multiple interfaces or a medium access mechanism such as CDMA. A large part of routing protocols assume that nodes communicate over a single logical wireless channel. Those protocols are generally CSMA/CA-oriented.

Structure: Routing protocols can be categorized as flat or hierarchical. In a flat protocol, all nodes play the same role in the routing scheme. Although such a protocol avoids the resource cost involved in maintaining a hierarchical structure, scalability may become an issue in large networks.
By opposition, hierarchical protocols use a hierarchical structure in order to reduce the number of nodes participating in the route computation and reduce the traffic overhead due to local movements of nodes. Typically, in a heterogeneous ad hoc network topology, devices have not the same capabilities in terms of processing capacity, radio range or battery life. So, the hierarchy enables to solve problems such as bottleneck. Unfortunately, significant resources are needed to impose a topological structure on a highly dynamic ad hoc network. In addition, a bad partitioning can have a huge negative performance impact.

State information: Some protocols are called topology-based meaning that nodes maintain topology information. Typically, in a link-state protocol, every node advertises its connectivity with each of its direct neighbors which in their turn advertise their direct neighbors. This process continues until all nodes know the entire network topology. Each node computes the shortest path to each destination (e.g., by using the Dijkstra's algorithm) and maintains it in its routing table. In short, each node makes the forwarding decision based on complete topology information.
Other protocols are destination-based protocols. In this case, the nodes do not maintain the entire topology but only information about their neighbors. Among destination based protocols, the most common ones are "distance-vector" protocols, which

maintain a distance (hop count) and vector (next hop) to a destination. Each node exchanges its distance to all other nodes with each of its neighbors. The drawback of such protocols is their slow convergence and the risk of loops in a dynamic environment.

Scheduling: Routing protocols can also be classified, in terms of triggering mechanism used to broadcast control messages, as proactive or reactive.
In proactive routing protocols, nodes exchange route information periodically or in response to topology change. All fixed network routing protocols are proactive. To reduce the traffic overhead in ad hoc network, reactive or on-demand routing protocols maintain routes only if they are used, and delete them after a period of time. In addition, nodes do not exchange periodical information but when one of them needs a route, it broadcasts a "route request" that is propagated from node to node until it reaches the desired route destination. Afterwards, the destination initiates a route reply back to the source. In this way, the route is traced. Unfortunately, this route discovery process implies a longer route latency and generates a important traffic overhead.

A given criteria has to be chosen according to the nature of the network topology. The advantages of routing protocol should match with the application requirements and the influence of the protocol drawbacks should be minor. For instance, in the context of a traffic intelligent application, in which each car represents a network's node, the scalability is critical whereas the need of fast route establishment is a secondary objective. In this case, an on-demand, destination based protocol is certainly the most suitable. Another example is military networks, soldiers, tanks, and command posts can be equipped with distinct wireless communications equipment and the communications must be engaged very quickly. Therefore, a hierarchical, proactive, topology-based protocol seems to be the best choice.

As time goes by, routing protocols are enhanced in order to support commercialization. Further researches are required to provide hybrid routing protocols that can adapt well to various environments. For example, an integration of hierarchical, table driven routing protocols with on-demand routing mechanism. Another emergent idea is inspired by the ant colony optimization (ACO) algorithm detailed in [OHHL05]. It proposes to find the optimal route by generating artificial ants. Those ants explore path and depose pheromone (depending on the node parameter measured, e.g., battery life, medium quality) along it. As time goes by, pheromone evaporates and the next generated ants will follow the path where the strength of pheromone is maximal. The probalistic selection of the paths allows searching large number of solutions.

For this project, the AODV routing protocol has been chosen to make ad hoc routing environment. The motivations for choosing AODV are that it constitutes a simple, loop-free and robust protocol. It does not create too much traffic overhead and is well known in the research community. In addition, some AODV implementations are available (e.g., Kernel AODV v2.2.2).

2.1.3 AODV

The Ad hoc On Demand Distance Vector (AODV) routing algorithm is especially designed to fulfill the ad hoc mobile network requirements. It is fully detailed in RFC 3561[C.P03]. This algorithm, that belongs to the Bellman-Ford algorithm family, exchanges information with its neighbors to discover new routes, and only keeps track of the next hop of a given route instead of the entire route. The control traffic messages are transmitted via UDP, meaning that some messages can be lost (no reliability). AODV is an on demand algorithm, it builds routes between nodes only when requested by source nodes. It maintains these routes as long as they are needed by the sources. AODV uses sequence numbers to ensure the freshness of routes. As already mentioned, it is loop-free but also self-starting, and scales up to large numbers of mobile nodes.

Request for a route

AODV builds routes using a route request (RREQ)/route reply (RREP) query cycle. When a source node desires a route to a destination for which it does not already have any one, it broadcasts a RREQ packet across the network (flooding). Nodes receiving this packet set up backward pointers to the source node in their routing table and re-forward this RREQ to their neighbors and so on until the RREQ reaches its final destination or an intermediate node that already knows a route to the destination.

Once the RREQ has reached such as node, it answers back a RREP to the originator of RREQ. This RREP will follow the road traced by the RREQ and so create a reverse path for data transfer.

Note that a major disadvantage of flooding is that a node receives back from its neighbors the RREQ that it has just sent. To avoid this problem, AODV proposes to just discard any RREQ that a node has already received. This mechanism is assured by the sender that maintains in its memory one 'RREQ id' which is incremented by one before each RREQ sending. This number and the IP's sender identify the RREQ so that a node can know if it has already received this RREQ or not.

To illustrate this mechanism, let us consider the topology on Figure 2.2. This ad hoc network topology consists in ten active nodes linked to each other. A node is darkened when it has received the RREQ and the arrows up on the link represent an active route. To focus on the network layer, suppose that the link between two nodes is bidirectional.

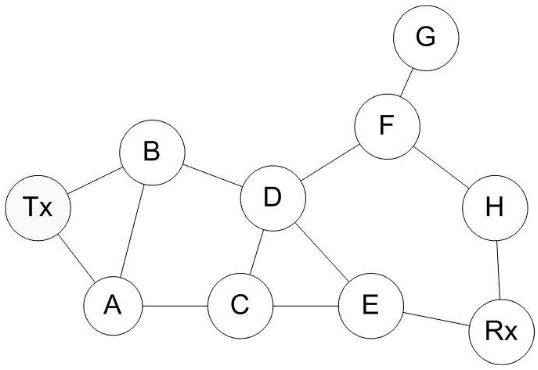

Figure 2.2: Illustration of flooding process (1/10)

Let us assume that the node 'Tx´ wants to send a message to the node 'Rx' and does not have any valid route in its routing table. Therefore, it increments its own 'RREQ id´ and creates the RREQ message with the field 'RREQ id´ set to its own one. Before broadcasting the RREQ, 'Tx´ buffers the field 'RREQ id' and the originator IP address of RREQ (its own address). In this way, when 'Tx' receives the request back from its neighbors, it will not reprocess and re-forward the RREQ. Finally it sends this RREQ through the network hoping to get a route to the node 'Rx' (Figure 2.3).

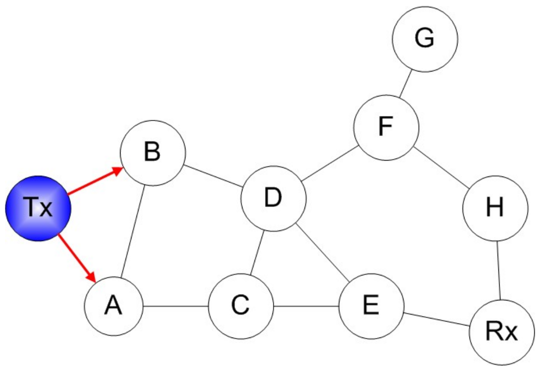

Figure 2.3: Illustration of flooding process (2/10)

When the nodes 'A' and 'B' receive the message, they first create a route to the previous hop 'Tx' in their routing table shown in Figure 2.4 by a 'Tx' label arrow. Due to the fields 'RREQ id' and 'Originator IP address' they can determine whether they had already received this RREQ. In this example, it is the first time they receive it and furthermore they do not have any route to the destination of RREQ. Therefore, they increment the 'hop number' field in the RREQ and broadcast it in their turn.

On Figure 2.4, the nodes 'Tx', 'B' and 'A' receive a second time the RREQ from some of their neighbors. They can simply discard the packet after having added a route or updated the routing table to the sender of this packet.

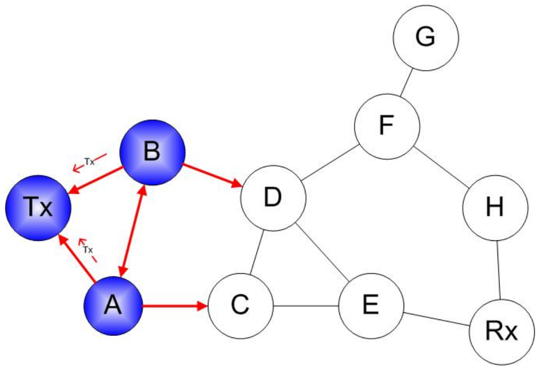

Figure 2.4: Illustration of flooding process (3/10)

As for the nodes ‘C’ and ‘D’, it is the same process as when ‘A’ and ‘B’ received the RREQ except that the nodes ‘C’ and ‘D’ do not have a reverse route to the originator of RREQ. This reverse route will be needed if the node ‘C’ or ‘D’ receives a RREP back to ‘Tx’. Therefore, before broadcasting the RREQ they must create the reverse route to ‘Tx’.

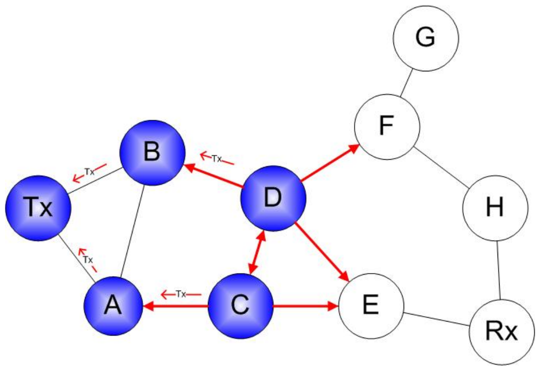

Figure 2.5: Illustration of flooding process (4/10)

The broadcasting process continues until the destination node receives the RREQ message or until an intermediate node has a route to the destination.

In this scenario, let us suppose the ‘Rx’ node receives the RREQ from the node ‘E’. Since the ‘Rx’ node is the ultimate destination it will answer the RREQ with a RREP message to the RREQ originator, i.e., the ‘Tx’ node. Note that the RREQ continues its dissemination until all the nodes receive it. More precisely, each RREQ has a ‘Time To Live’ (TTL). So, if a node receives a RREQ with a TTL equal to 0 then it discards it. Whenever the originator node does not receive any RREP in response to its RREQ, it will initialize a new request with a higher TTL. It will retry to send a RREQ for a fixed number of times after which, if it has not received a response, it will declare the destination host unreachable. This mechanism is useful to reduce the signalling traffic in the ad hoc network.

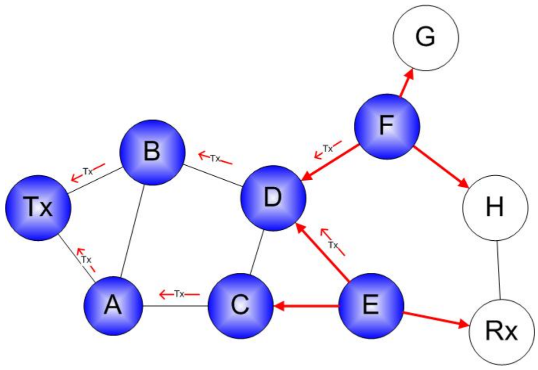

Figure 2.6: Illustration of flooding process (5/10)

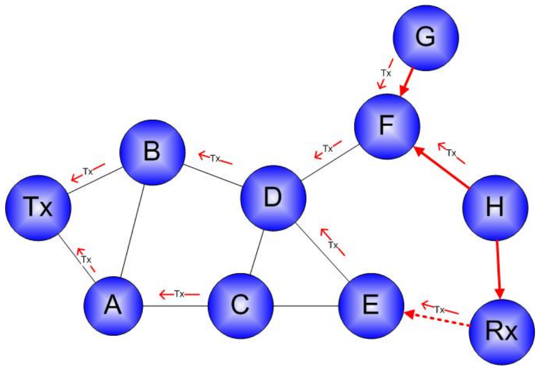

Figure 2.7: Illustration of flooding process (6/10)

The dotted line in Figure 2.7 shows the RREP unicasted to the next hop towards 'Tx', i.e. the originator of RREQ. This RREP will follow the route that was created by the previous RREQ. Each node on the RREP path from 'Rx' to 'Tx' will update its routing table by creating a route to 'Rx' via the previous hop (showed on Figure 2.8 by an arrow within the label Rx).

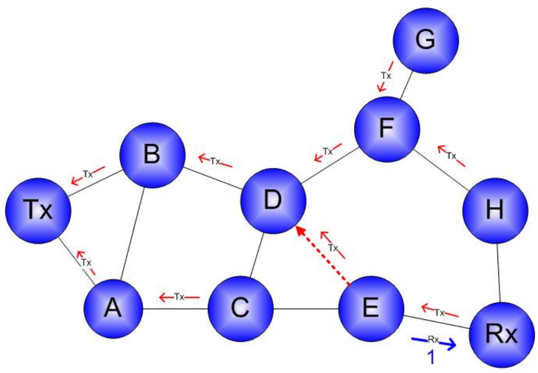

Figure 2.8: Illustration of flooding process (7/10)

At each hop, the 'Hop Count' field in RREP is incremented by one, so that when the RREP reaches 'Tx', the 'Hop Count' will represent the distance from 'Tx' to 'Rx' as shown on the Figure 2.9.

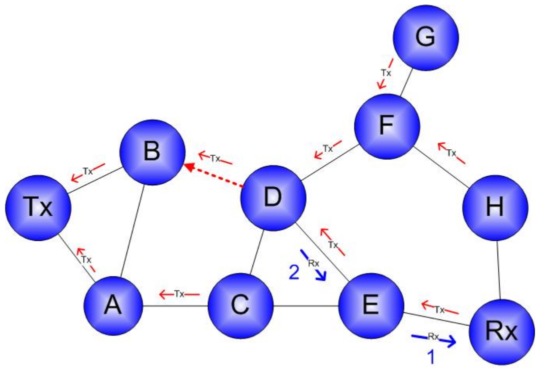

Figure 2.9: Illustration of flooding process (8/10)

Most of the time, in wireless communication, the RREP message reaches faster its destination node than the RREQ message. Indeed, the flooding may cause many packet collisions and then considerably increase the time to reach the final destination node.

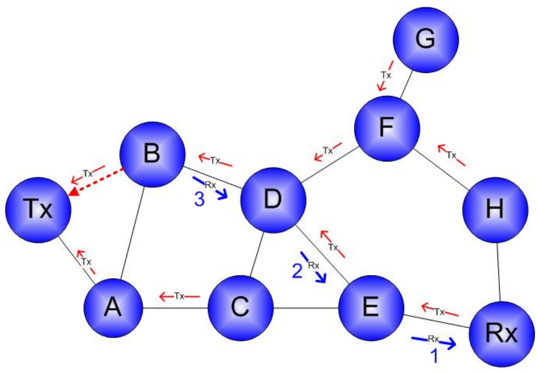

Figure 2.10: Illustration of flooding process (9/10)

In this scenario, the 'Tx' node finally receives the RREP from the node 'B' (Figure 2.10). So, the forward route from 'Tx' to 'Rx' is complete and ready for data transfer as long as the route remains active (Figure 2.11). A route is considered active as long as data packets travel periodically from the source to the destination along that path. Once the source stops sending data packets, the links time out and will eventually be deleted from the intermediate node routing tables.

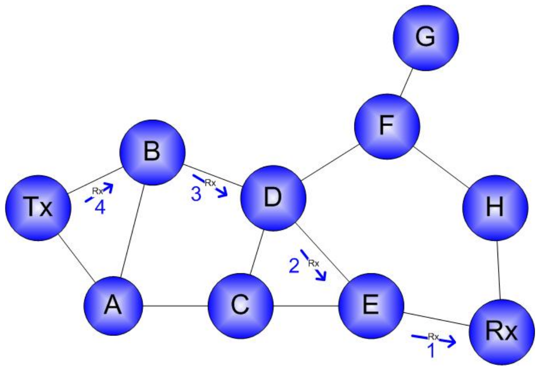

Figure 2.11: Illustration of flooding process (10/10)

Error messages

The Route Error Message (RERR) allows AODV to adjust routes when the nodes move. Whenever a node receives RERR it looks at the routing table and removes all the routes that contain the bad nodes. The RFC 3561 [C.P03] specifies three scenarii for which a node generates a RERR:

1. A node detects that it cannot communicate with one of its neighbors. When this occurs this first node looks in its routing table for the routes that use the unreachable neighbor for as the next hop and marks them as invalid. Next, it broadcasts a RERR for this neighbor and for all destinations routes now marked "invalid".
2. A node receives a data packet that it is supposed to forward, but for which it does not have a route to the destination.
   The real problem is not that the node does not have any valid route but that some other nodes think that the correct route to the destination goes through that node.
3. A node receives a RERR from a neighbor for one or several active route(s) in its routing table. If this happens, this node must invalidate them and re-broadcast the RERR in order to inform its neighbors which are using those routes.

Routing loop problem

Let us consider the topology on Figure 2.12 representing an ad hoc network with many nodes though the sole 'A', 'B', 'C', 'D' and 'E' nodes are shown on the picture. The nodes 'D' and 'E' are neighbors and the links that are drawn as dotted lines mean there is a path between these two nodes. We also consider the node 'A' knows a route to 'E' via 'D'. Now, imagine the node 'E' moves out of node 'D' 's range. Then, when 'D' detects the link failure, it should notify its neighbors with a RERR message about 'E'. But suppose this

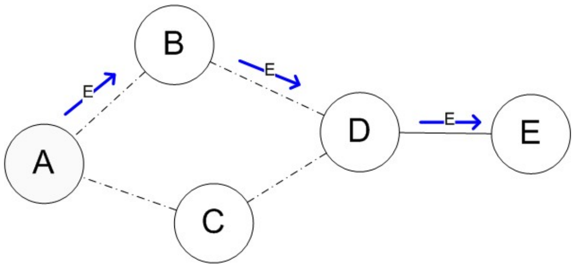

Figure 2.12: Illustration of loop problem (1/5)

RERR is lost before reaching ’A’ as figured in the Figure 2.13. This situation can occur more often than expected because UDP does not assure any reliability. Then, when ‘D’

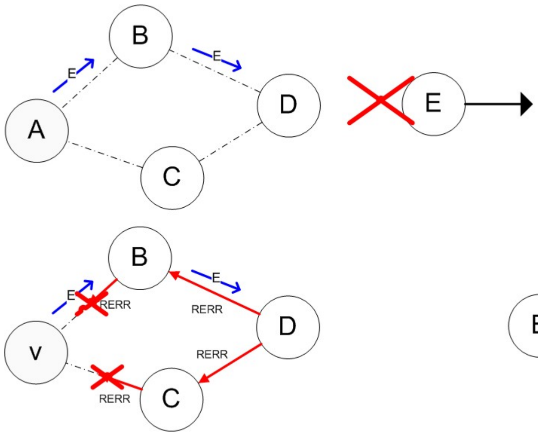

Figure 2.13: Illustration of loop problem (2/5)

wants to send a message to ‘E’, it broadcasts a RREQ because it does not have any valid route to that ‘E’ destination (Figure 2.14). The RREQ reaches the node ‘A’ via the node

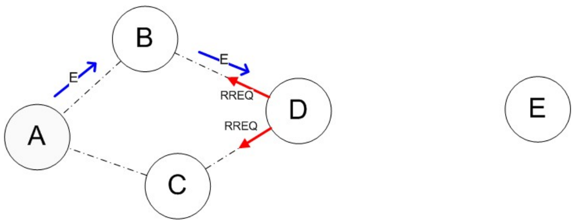

Figure 2.14: Illustration of loop problem (3/5)

‘C’, and ‘A’ answers the RREQ since it has a route to ‘E’ via next hop ‘B’ (Figure 2.15). Finally the node ‘D’ receives the RREP and now, believes there is a route to ‘E’ via the next hop ‘C’. The result is the loop ‘D’, ‘C’, ‘A’, ‘B’, ‘D’ (Figure 2.16).

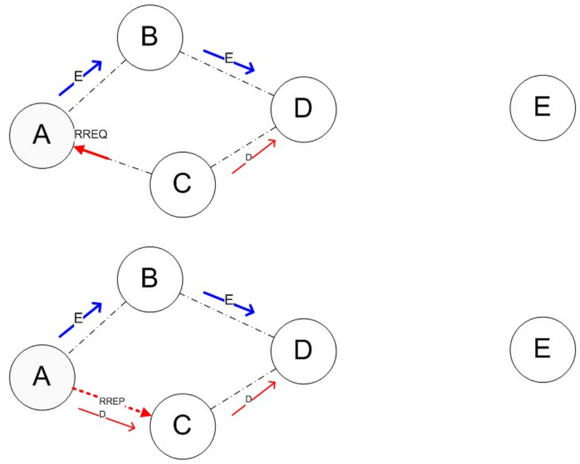

Figure 2.15: Illustration of loop problem (4/5)

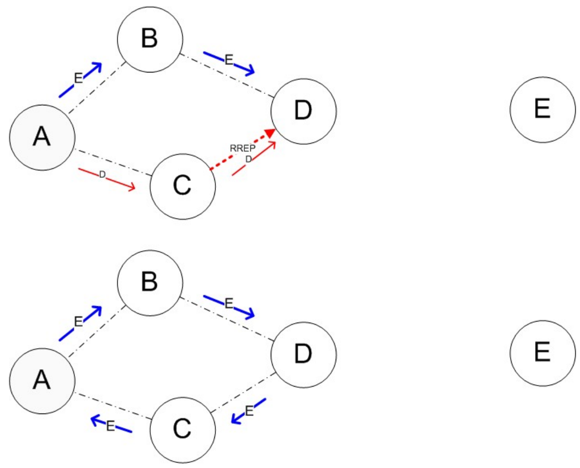

Figure 2.16: Illustration of loop problem (5/5)

Sequence number

AODV proposes to overcome this problem by using sequence numbers: each node of the network owns a sequence number (Originator Sequence Number-OSN) that acts as a time stamp and is incremented each time the node sends a new AODV traffic message. Moreover, each route in the routing tables has the latest known sequence number about its destination (Destination Sequence Number-DSN). When a message is created (RREQ or RREP), the originator puts its OSN and the latest known DSN of the destination.
The first number is used by intermediate nodes to prevent conflicts with previously established reverse route (to the RREQ originator). The second number is used by an intermediate node if it has already an active route to the final destination. Indeed, if its DSN for the desired destination is higher than the DSN of the RREQ, the node creates a RREP message and unicasts it to the source node and does not forward the RREQ.

Otherwise, if the entry in its routing table has a lower DSN than the DSN of the RREQ, the node forwards the RREQ. In this case indeed, the originator knowledge about the destination is 'fresher' than the forwarding node's.

For RERR messages, the system is slightly different. Indeed, the sender does not put its OSN but rather looks at the last DSN corresponding to the entry of routing table for the destination that has become unreachable and increments it before sending the RREQ. In this way, it expresses it has new information about the unreachable node. To keep AODV in good working order, each node has to maintain its routing table. Indeed, when a node receives an AODV control message, that node has to update its information about certain routes but only if the sequence number in the message is higher than in the routing table's. For instance, if a node receives a second RREP as answer to its previous RREQ with a smaller hop count it may update its routing information for that destination only if this new RREP has a higher OSN than the corresponding one in its routing table.

Connectivity with neighbors

Periodically, each node broadcasts 'Hello' messages towards its neighbors in order to keep its direct connectivity up to date. These messages contain both the IP address of the emitting node and its current sequence number. To avoid that these messages are forwarded from the node's neighbors to third parties 'Hello' messages have a TTL value of '1'.

2.2 Physical layer

In an ad hoc environment like in any other shared medium system, the physical layer design is of importance because each network's node communicates through a same wireless medium. To improve signal recognition performance, engineers develop new modulation and coding techniques but also try to improve antenna design.

This section gives an intuitive overview of phenomena that occur in a wireless environment and its consequences on signal quality. Afterward, concepts of beamforming and adaptive array antenna will be described.

2.2.1 Wireless channel

In a wireless mobile communication, a signal can travel from transmitter to receiver over multiple reflective paths. These reflections can cause fluctuations in the received signal amplitude, phase and direction of arrival, giving rise to the terminology of '**multipath fading**' [Con03].

There are two types of fading effects [Skl97]:

Large-scale fading The large-scale fading represents the average signal power attenuation or the path loss due to the motion over large areas. This phenomenon is affected by significant field elements (hills, forests, clumps of buildings, large billboards, etc.) between transmitter and receiver. The statistics of large-scale fading provide a way to compute an estimate of the path loss as a function of the distance

Small-scale fading Small-scale fading refers to local dramatic changes in signal amplitude and phase that can be experienced as a result of small changes (as small as a half-wavelength) in the spatial separation between transmitter and receiver. The small-scale fading is also called Rayleigh fading because if the multiple reflective paths are numerous and if there is no line of sight signal component, the envelope of the received signal is statistically described by a Rayleigh probability distribution.

This section focuses on small-scale fading and its implications for the received signal.

RF propagation

Several physical phenomena affect the signal propagation. Hereunder stands a list of them with a short explanation:

Reflection it appears when a propagating electromagnetic wave impinges upon an object whose dimensions are very large compared to the wavelength of the RF signal. Reflections are typically caused by the surface of the earth and by buildings and walls. An example is shown on Figure 2.17.

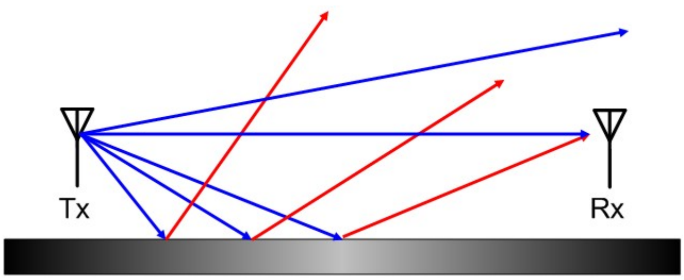

Figure 2.17: Example of reflection

Diffraction Diffraction occurs when the radio path between transmitter and receiver is obstructed by a dense body that has sharp irregularities and large dimensions compared to the signal wavelength. The Huygens principle of wavelets can be used to explain that phenomenon: “each point on a wave front acts as a source of secondary wavelets”, so the combination of these secondary wavelets caused by irregularities and sharp forms produce new waves in the direction of the initial propagation. Diffraction is a phenomenon that accounts for RF signals travelling from transmitter to receiver without a line of sight between both. It is often called ‘shadowing’ because the diffracted signal can reach the receiver even if it is shadowed by an impenetrable obstacle.(2.18)

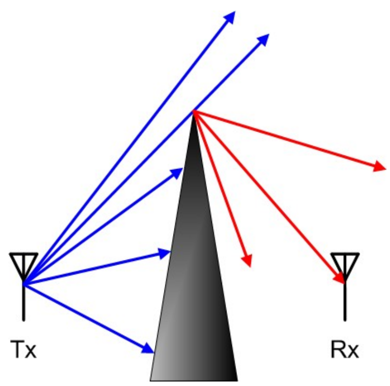

Figure 2.18: Example of diffraction

Scattering Scattering occurs when radio waves collides with objects of small dimensions compared to the wavelength, and when the number of irregularities per unit volume is large, causing the reflected energy to spread out in all directions. In practice, foliage, street signs, lampposts, etc. induce scattering in mobile communications systems (Figure 2.18).

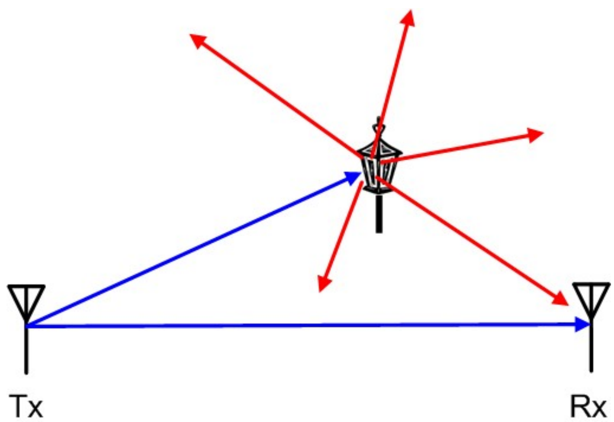

Figure 2.19: Example of scattering

Multipath interference

Due to the above listed phenomena, the signal reaching the receiver contains not only a direct line of sight radio wave, but also a large number of reflected radio waves (Figure 2.20).

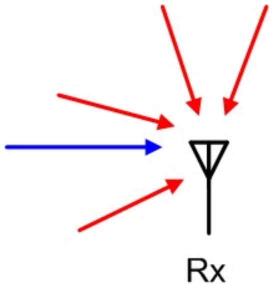

Figure 2.20: Multipath rays

These replica waves can have a different attenuation and a time delay (due to the different paths they have taken) meaning for the receiver a different amplitude, a different direction of arrival and a different phase, causing a significant degradation of the signal quality and subsequently diminishing the global performance of the wireless network. Figure 2.21 illustrates the effect of multipath interference.

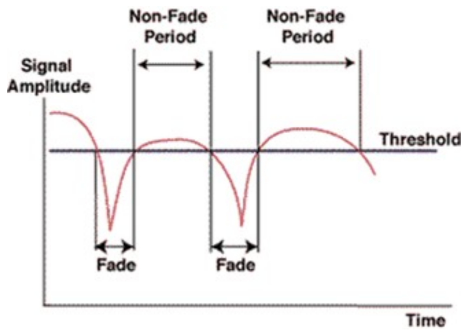

Figure 2.21: Effect of multipath interference on an user signal

Channel fading is experienced as an unpredictable, stochastic phenomenon changing by space and time, and producing both constructive and destructive interferences.
If at one point, the waves of multipath signals are out of phase, then degradations of the signal occur resulting in a so called 'fade period'. Indeed, just think about the composition of two identical signals being totally out of phase (180° shift): they neutralize each other. On the other hand, when the multipath signals are aligned in phase, the signal attenuation is null producing a 'non phase period'.

In short, the received signal strength will fluctuate downwards, causing a temporary, but periodic, degradation of signal quality (Figure 2.21). So the receiver can occasionally lose temporarily the signal, even if the average signal power propagating through the area is sufficient. The wireless networks should be designed in such way that the adverse effect of fading is minimized.

2.2.2 Adaptive Array Antenna

An adaptive array antenna (AAA, Figure 2.22) consists of an array of antenna elements and a real-time adaptive processor that adjusts the element weights so that the antenna output is maximized for some desired signal in the presence of interference, noise and fading phenomena [J.E03]. In the literature, this technique is also known as adaptive beamforming or spatial diversity.

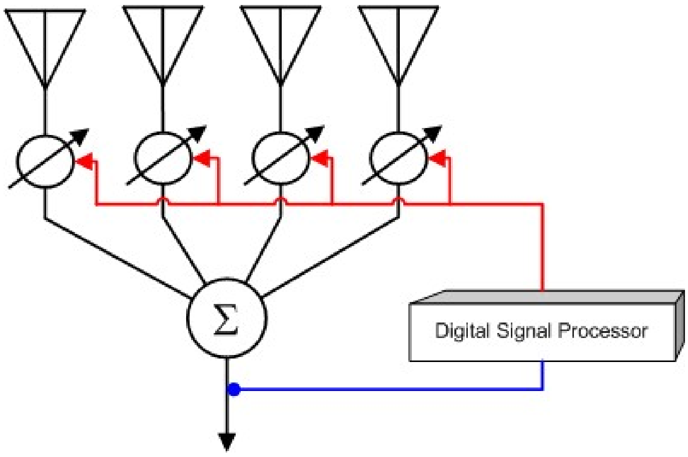

Figure 2.22: Adaptive Array Antenna with 4 elements

Directional antenna

It is possible to create a directional antenna by just combining two omni-directional antennas separated by a distance of $\lambda/2$ where λ is the wavelength of considered signal (Figure 2.23).

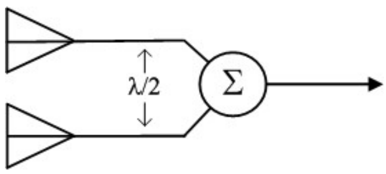

Figure 2.23: 2-element array Antenna

Let us examine what happens when that antenna receives a signal coming from different directions.

1. If the transmitter is located broadside to the plane of the antennas, each antenna receives a plane wave with the same phase because there is precisely the same distance between the transmitter and each antenna. The output of the antenna has therefore two times more amplitude (four times more power).

2. If the transmitter is located end-fire to the plane of the antennas, the second antenna will receive the plane wave with a phase shift. λ is indeed the distance the wave needs to make an oscillation and the interval between antennas is $\lambda/2$. Therefore, between double antenna, the wave can only make half an oscillation (Figure 2.24). Since the

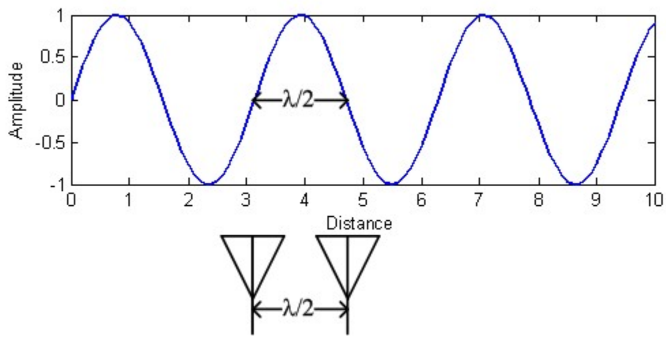

Figure 2.24: Phase shift between the elements of a double antenna

two antenna signals are in phase opposition, the combination of both output is null (the signals neutralize each other).

It could be interesting to see what are the performance of this simple 2-element array antenna in comparison with a single omni-directional antenna. RF engineers use the gain of the antenna for this purpose. The gain is the measurement of the ability of an antenna to amplify the incoming wave signals from a particular direction, compared with the sensitivity of an isotropic antenna that receives equally well from each direction. Both measurements are measured in decibels and are equal to:

$$\boxed{\text{Gain} = 10 * \log_{10}(\frac{PowerOUT}{PowerIN})[dB]}$$

- A **positive gain** for one direction means that a **larger** fraction of the radiated power is received or transmitted in this direction than with an isotropic antenna.
- A **negative gain** for one direction means that a **smaller** fraction of the radiated power is received or transmitted in this direction than with an isotropic antenna.

The gain is usually represented as a circular graph indicated by the distance from the center for the corresponding angle. This graph is called '**radiation pattern**'. Figure 2.25 shows the radiation pattern for the two elements array and the standard isotropic antenna.

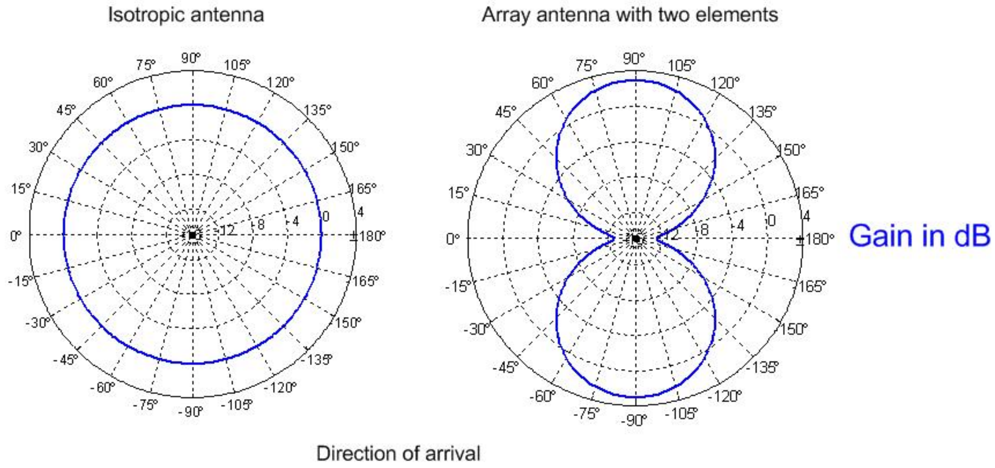

Figure 2.25: Radiation pattern

The hole formed by the negative gain is called **null** and the lobe formed by the positive gain is a **peak**.
The radiation pattern can also be interpreted as the signal intensity radiated when current is set on the antenna due to the antennas reciprocity property. But this pattern should not be confused with the **coverage pattern** that represents the physical area where the signal is still strong enough to be received (modulation threshold).

Adaptive array antenna

Therefore, even if there is no directivity for each antenna (considered separately), it is possible to generate a certain directivity when combining several antennas.

In the previous array antenna, the phase difference is caused by the physical position of element antenna. The possibilities of this kind of device are however very limited and not convenient for the user, who must physically point the array in the direction of signal arrival. More rapid and flexible results are obtained by electrically weighting the outputs of each element before summation, while weights adjustment will change the radiation pattern. This is the main idea of an adaptive array antenna that uses a **digital signal processor** (DSP) to electronically adjust the weights to produce the desired AAA output. More precisely, the DSP can control automatically - thanks to an algorithm - the phase of the incoming signal to maximize the desired signal and cancel (or at least minimize) an eventual interference (Figure 2.26).

When receiving a signal, beamforming can increase the gain in the direction of wanted signals and decrease the gain in the direction of interference and noise. This technology brings a new dimension, "space", in addition to time and frequency. The AAA is used like

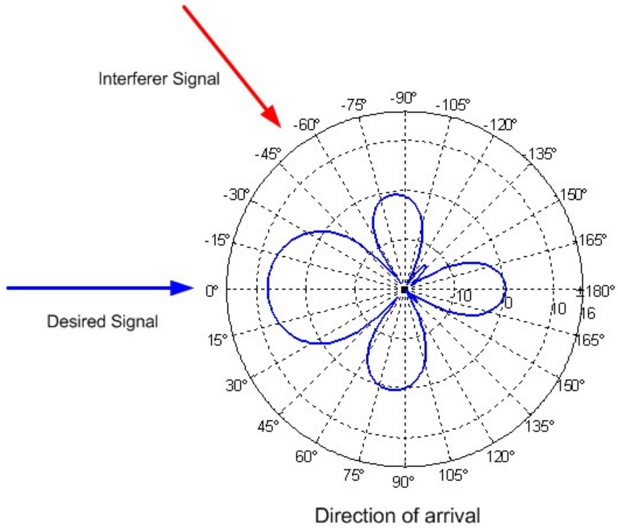

Figure 2.26: AAA behavior

a **spatial filter** allowing the terminal to favor one or several direction(s) against others. Obviously, the more elements compose the AAA the more precise and flexible the filter is.

2.3 AODV enhanced with adaptive array antenna

This project aims to demonstrate how AAA could improve the performance of ad hoc networks. It is obvious that the AAA extends the possible coverage surface of each node but how AAA deals with the fading is an issue to study.

Let us consider the city topology depicted on Figure 2.27 where the circles represent terminals and a connection between two nodes mean that they are neighbors. Let us suppose that ‘A’ wants to communicate with ‘E’. Thus node ‘A’ initiates a RREQ which is received by ‘B’ and ‘C’. Because of the numerous buildings between the nodes ‘B’ and ‘E’, the fading effect due to multipath phenomenon is high. In other words, if the terminals are equipped with omni-directional antennas, there is no connection possible between ‘B’ and ‘E’. Therefore, ‘B’ can not forward the RREQ. By opposition nodes ‘A’ and ‘C’ are neighbors since there is no building between them. So, the flooding process continues via ‘C’ until to reach ‘E’ which sends a RREP back to ‘A’. In this way, with omni-directional antenna, AODV founds the route ‘A-C-F-H-G-E’ with a hop count equal to 5.

Now, let us consider the same topology but let us equip the node ‘E’ and ‘B’ with an AAA. We can expect to have a reduction of fading phenomenon enabling to node ‘E’ to have a connection with ‘B’. Indeed, electronically, the ‘E’s AAA is able to form and direct the main lobe sensitivity in the direction of ‘B’ as soon as it transmit the RREQ (Figure

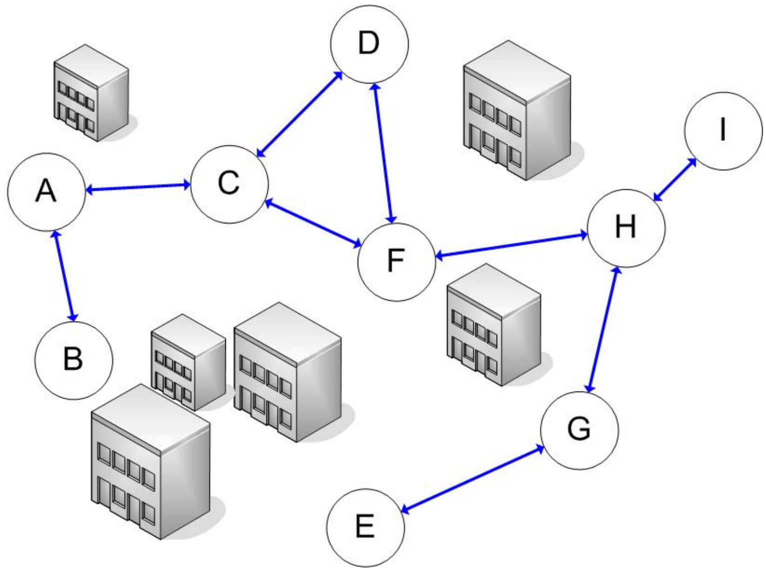

Figure 2.27: AODV behavior with high fading environment

2.28). The same principle is valid when 'E' sends back the RREP. Finally, the route found by AODV should be 'A-B-E' with a hop count equal to 3. So, AODV does not lose its way through the entire network, hence reducing the magnitude of "flooding storm" and providing shorter routes.

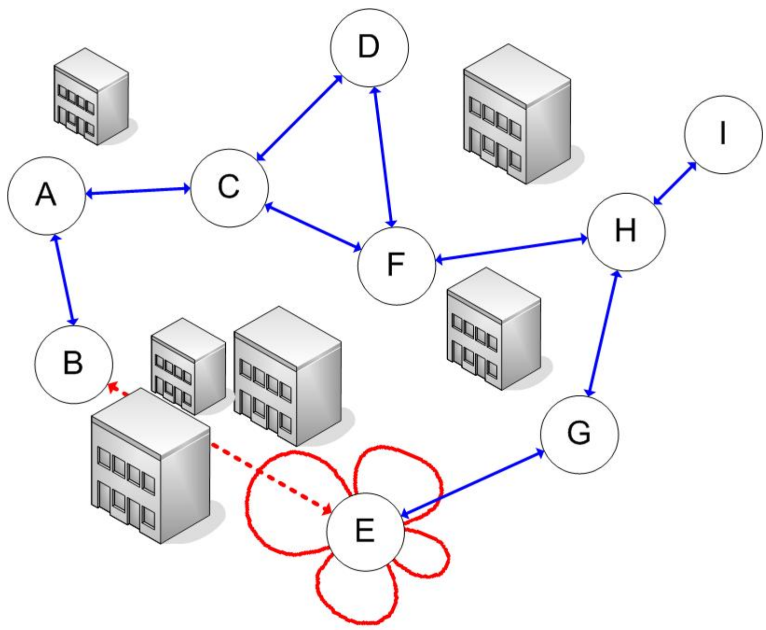

Figure 2.28: AODV behavior with high fading environment and AAA

Accordingly, the goal of this project is to study through simulations how AAA can compensate the fading phenomenon. This capacity will help preventing critical situations previously described.

2.4 Applications

Since ad hoc networks are flexible networks that can be set up anywhere at any time, without infrastructure (neither centralized administration nor pre-configuration) people have come to realize the commercial potential and advantages that mobile ad hoc networking can bring.

Mobile ad hoc networks have primarily been used for tactical network-related application to improve battlefield communication and survivability. The dynamic nature of military operations means that it is not possible to deploy fixed infrastructure. In addition, pure wireless communication has the limitation that radio signals are subject to interference and radio frequencies higher than 100 MHz rarely propagate beyond line of sight [BS04].

On the other hand, the introduction of new technologies such as Bluetooth, IEEE 802.11 facilitate the deployment of ad hoc technology outside of the military domain. As a result, many new ad hoc applications have been conceived including typically PAN (Personal Area Network), home networking, search and rescue operations, customer's application indoor, outdoor and sensor networks.

Because of the higher cost in AAA manufacturing and the limited devices size, the use of AAA in ad hoc network applications is more or less suitable depending on the scenario. Let us focus on some ad hoc networks applications where AAA can improve the performance.

We can imagine a sensor network that monitors patients inside an ambulance and this ambulance communicates patient's information to the hospital. First, sensors network collects patient's information such as patient's identity, blood group, artery pressure, temperature, symptoms and so on. Then, the ambulance transmits data to the hospital in such way that the emergency department can prepare the arrival of patient (room, drugs, specialist doctor and so on). Besides, all ambulances, fire brigade or police vehicles belong to an ad hoc network. If the ambulance is too far away from the hospital, other vehicles relay information in order to inform hospital as soon as possible (Figure 2.29). In a city environment, the use of AAA is really interesting since there is a large amount of vehicles and fading effect is important.

In the previous description, the ad hoc network operates in standalone mode. In other words, it does not require any broadband access. On the contrary, the most promising application of ad hoc networks is certainly the enhancement of existing fixed-backbone.

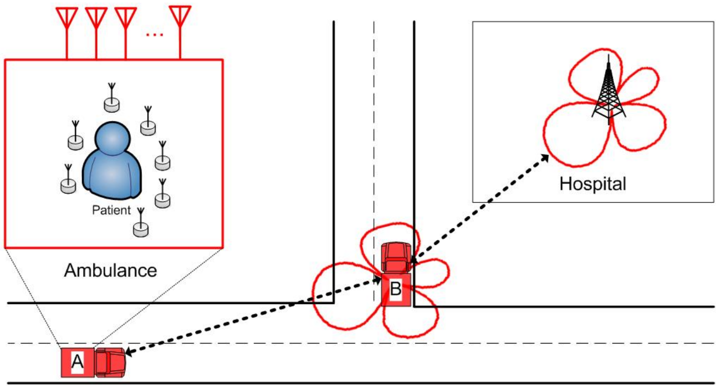

Figure 2.29: Ad hoc network and AAA used to notify emergencies to hospital

Typically, even within a well-designed cellular fixed-backbone, there are some locations that are not covered by antennas either because of short term or long term outages or because the layout of pylons is not perfectly arranged. Ad hoc networks can address the lack of flexibility, complexity and excessive cost of infrastructures by providing extended coverage.

For example, in a 4G network vision [BS04], networks will be entirely packet switched using protocols evolved from those in use in today's Internet. In "all over IP-networks", mobile telephony will be supported by using available VoIP set of protocols such as SIP [Ros02] or H.323. [Lev03]
With this assumption, let us consider the cellular topology on Figure 2.30. Fixed infrastructures have two wireless interfaces. The first interface is used to communicate with other fixed antennas and the second one, equipped with AAA, is used to communicate with mobile phones. In addition, mobile phones are able to relay packets either to another mobile phone or to the fixed infrastructure which it is connected. In this way, the considered topology forms an heterogenous ad hoc network. Recent ad hoc network routing protocol developments support options to allow certain nodes to be preferred over others in a neighborhood [VGLL05]. In this case, fixed infrastructure will be privileged for the routing functionality while mobile devices operating with limited energy will be low-preference routing nodes.

Let us suppose that the mobile 'C' desires to communicate with 'B' but 'C' is out of range of cellular basic grid. Without AAA or ad hoc routing functionality between mobile phones, the communication can not be established. Nevertheless, by adapting the directivity of AAA number 1, the 'C' 's request is accepted. This AAA relays the communication via AAA number 2 which delivers it to mobile 'B' since it is located in the cellular basic grid.
While the communication is going on, mobile 'D´ wants to engage a communication with 'A'. In this case, 'D' cannot directly relay packets to AAA number 1 because it is really

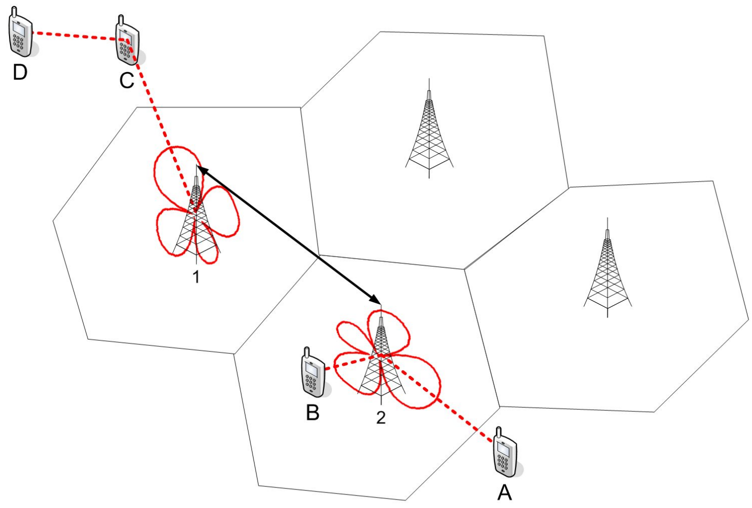

Figure 2.30: Ad hoc network and AAA used to enhance fixed architectures

too far from it. More precisely, fixed AAA number 1 cannot adapt its directivity because the 'D' signal strength is too weak. However, ad hoc network functionality allows 'D' to transmit packets to mobile 'C' that will forward them to the fixed AAA number 1. To reach mobile phone 'A' fixed AAA number 2 has to adapt its directivity towards its direction.

When an outage occurs in a fixed infrastructure because of earthquake, storm or any technical failure, by using ad hoc networking concept, the system still provides a minimal service and achieves thus increased reliability.

Roughly the use of AAA is really interesting in an ad hoc context where nodes are very far each other or/and where the fading effect is important. Moreover, AAA can overcome the lack of adaptability and efficiency of the ad hoc routing algorithms.

Chapter 3

Signal processing

The concept of AAA has been described in the previous chapter. Now, to deeply understand its behaviour, a mathematical formulation shall be defined including the theory of optimal weights.

Beforehand, this chapter proposes an introduction to the theory of signal and modulation/demodulation process. Especially, the Binary Phase Shifting Key (BPSK) modulation which has been chosen in the simulations will be detailed.

Note that this chapter derives from the reading of [Y.K05]. However, the following text has been largely completed with external sources.

3.1 Formulation of signal

3.1.1 Terminology

In the information theory, a signal is the sequence of states of a communication channel that encodes a message. In a communications system, a transmitter encodes a message into a signal, which is carried to a receiver by the communication channel [Aut]. For instance, a signal is an impulse or a fluctuating electric quantity, such as voltage, current, or electric field strength, whose variations represent coded information.

A signal can be periodic (e.g., having a shape of sinusoid) or aperiodic. In this document, the question of aperiodic signals is not tackled. A periodic signal is defined by:

Amplitude A is the measure of the magnitude of the maximum disturbance in the medium during one wave cycle

Period T is the time for one complete cycle of the oscillation of a wave and is measured in seconds (s)

Frequency f is the number of periods per unit of time (for example one second) and is measured in hertz (Hz)

Wavelength λ is the distance covered by the wave during one period and is measured in meters (m)

Velocity υ wave propagation speed. We consider it equal to $3 * 10^8$ m/s (speed of the light)

Phase ϕ determines the sine wave's behavior at the origin. The phase between two identical signals is the ratio of the timing difference to the period of time it is measured in radian degrees.

Those factors are related by these expressions:

$$T = \frac{1}{f} \tag{3.1}$$

$$\lambda = \nu * T \tag{3.2}$$

A signal (periodic or aperiodic) is represented as a function $s(t)$ where t represents the time and $s(t)$ the intensity of disturbance (Figure 3.1).

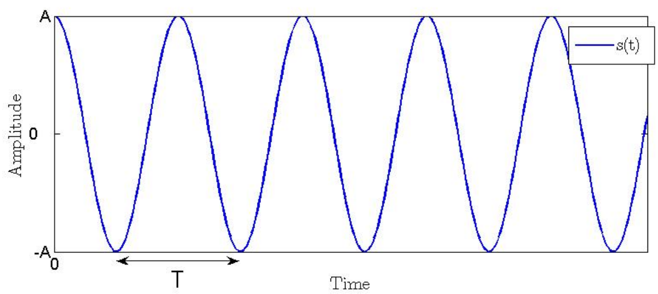

Figure 3.1: Graphical expression of periodic signal according to time

The definition of wavelength and the equation (3.2) enable to define the signal like a function of the distance (Figure 3.2).

The two axes of function $s(t)$ can take continuous or discrete values revealing in this way the differences between analog and digital signals. Indeed, an analog signal (Figure 3.3) is a function defined on two continuous axes and a digital signal (Figure 3.4) is a function defined on two discrete axes. Typically, speech is an analog signal which produces

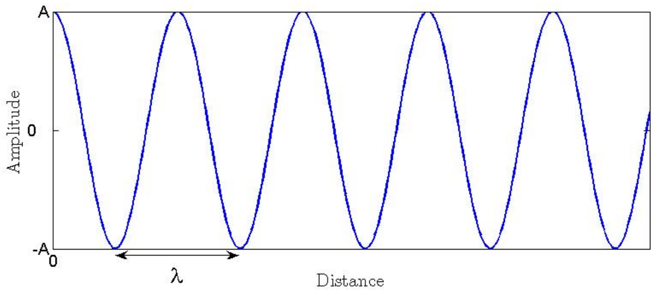

Figure 3.2: Graphical expression of periodic signal according to distance

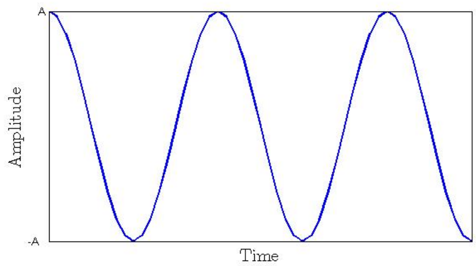

Figure 3.3: Analog signal

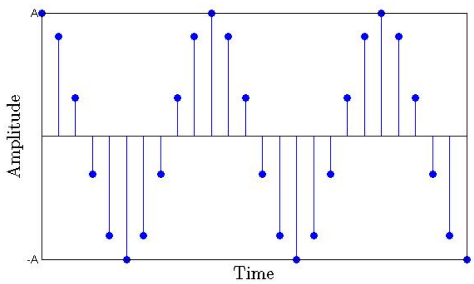

Figure 3.4: Digital Signal

pressure waves propagating in the air and, by opposition the sound information burnt on a CD forms a digital signal.

Although analog systems are less expensive in many cases than digital ones for the same application, digital systems offer much more efficiency, better performance, and much greater flexibility. Consequently, with the increased speed of digital computers, the development of increasingly efficient algorithms, and the ability to interconnect computers to form a communications infrastructure, digital communication is now the best choice for many situations [Joh05]. So, in order to process the signal with a computer it is needed to use an analog to digital converter which performs two consecutive processes: **sampling** and **quantization**.

Sampling The sampling consists in representing a signal waveform as a series of numbers which represents the measurement of signal's amplitude, taken at regular intervals transforming, in this way, the time domain in discrete values. The sampling rate (or frequency) is the main critical parameter in the sampling process. The Nyquist-Shannon sampling theorem tells that sampling frequency must be at least twice the maximum frequency component of the signal. Otherwise, the original signal cannot be recovered from the sampled signal. This phenomenon is called aliasing and is shown on Figure 3.5. The dotted line represents the original analog signal and the dots along this line result from the sampling process. When the sampled signal will be recovered, the signal reconstructed from the dots will not correspond with the original one.

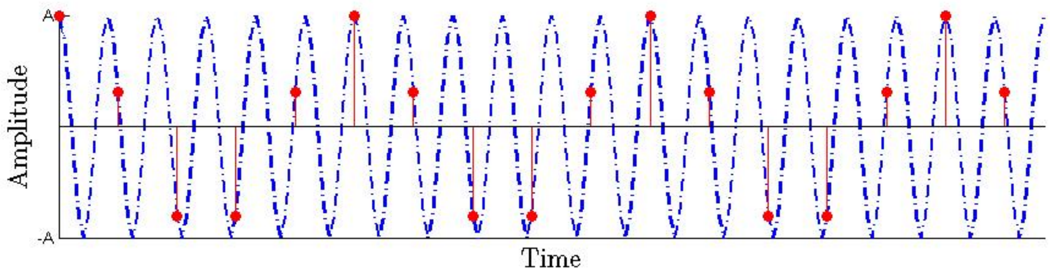

Figure 3.5: Illustration of the aliasing phenomenon

Quantization The quantization is the second step in the analog to digital conversion process, it approximates each sampled amplitude on a grid of predetermined fixed values. In other words, it converts the amplitude axis into discrete values. For a given dynamic, the more numerous quantization bits are, the smaller is the quantization interval and in the same way, the more accuracy is the quantization process. For instance, if the amplitude axis have to be decomposed in 16 slots, then each signal sample have to be quantized with 4 bits (Figure 3.6).

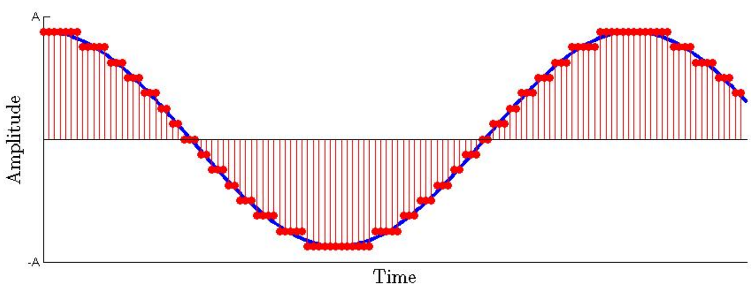

Figure 3.6: Quantization process with 4 bits

By way of illustration, an audio compact disc (CD) is sampled at 44,100 Hz and quantized with 16 bits.

3.1.2 Trigonometric expression of signal

Mathematically, the periodic sinusoid signal wave can be fully expressed by the function 3.3.

$$s_y(t) = A \sin(2\pi f t + \phi) \tag{3.3}$$

By another way, it can be expressed by a vector (vector Z on Figure 3.7) spinning around in a two dimensional Euclidian plane. More precisely, the amplitude (A) is the length of the vector, the frequency (f) is how many times the vector rotates and the phase (ϕ) is the original angle of vector from abscissa. We can see that the expression (3.3) results from the mapping of the vector on the vertical axis (y). By the same way, the equation (3.4) expresses the vector rotation by a similar mapping on the horizontal axis (x).

$$s_x(t) = A \cos(2\pi f t + \phi) \tag{3.4}$$

Those two first expression of signal ($S_x(t), S_y(t)$) are called the signal quadrature components.

3.1.3 Analytic expression of signal

The term "analytic signal" refers to the mathematical expression of the signal using complex numbers. Thanks to Euler's theorem, the vector (representing the signal) can be expressed in $\mathbb{C}$.

Indeed, Euler's theorem shows a deep relationship between the trigonometric functions and the complex exponential function.

$$\boxed{\forall \phi, \qquad e^{j\phi} = \cos\phi + j\sin\phi}$$

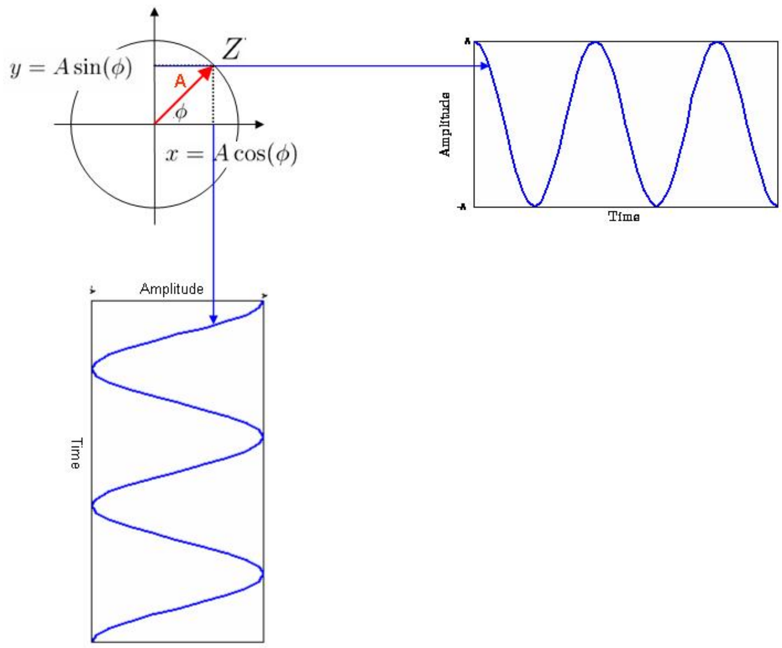

Figure 3.7: Expression of the signal like a vector in motion

Consequently, the previously defined vector Z can be expressed in the complex plane (Figure 3.8):

$$\left.\begin{array}{l} x \in \mathbb{R} \\ y \in \mathbb{R} \end{array}\right\} Z = x + jy \quad \in \mathbb{C}$$

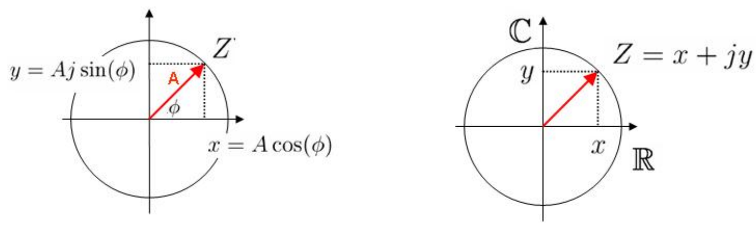

Figure 3.8: Vector in the complex plane

$$\begin{array}{rcll} Z & = & x + jy & \\ \Leftrightarrow \quad Z & = & A\cos\phi + Aj\sin\phi & \\ \Leftrightarrow \quad Z & = & A(\cos\phi + j\sin\phi) & \\ \Leftrightarrow \quad Z & = & Ae^{j\phi} & \text{(Euler's theorem)} \end{array}$$

Now in order to express the circular movement of the vector (speed), remember the *Trigono-*

metric expression of signal. Then, the analytic signal expression becomes:

$$s_Z = Ae^{j(2\pi ft+\phi)}$$

The analytic form is more convenient and simple than the trigonometrical one. Due to the property of exponential functions, the amplitude, the phase and the frequency can be expressed separately:

$$\begin{aligned} s_Z &= Ae^{j(2\pi ft+\phi)} \\ s_Z &= \underbrace{Ae^{(j\phi)}}_{\text{Complex envelope}} \quad \underbrace{e^{(j2\pi ft)}}_{\text{Carrier}} \end{aligned}$$

Since modulation puts bits on the phase or on the amplitude or on both in digital communication, this simplicity is very important. Usually, in digital communication, the complex envelope term conveys information and the carrier does not convey anything but plays a role to “lift up” the frequency of the signal. It is needed to radiate efficiently the energy from an antenna.
Note that the real signal can be derived from the analytic signal:

$$s_x(t) = A\cos(2\pi ft + \phi) = Re[Ae^{j(2\pi ft+\phi)}],$$

the amplitude of the signal (length of vector) equals

$$|Z| = \sqrt{x^2+y^2} = \sqrt{(x+jy)(x-jy)} = \sqrt{ZZ^*}$$

and the power equals

$$|Z|^2 = x^2 + y^2 = ZZ^*$$

3.1.4 Power Spectrum overview

Fourier analysis

Fourier claims that all periodical signals can be composed by a superposition of an infinite number of sine and cosine functions [Bel98]:

$$s(t) = A_0 + \sum_{k=1}^{\infty}\left[A1_k \cos\left(\frac{2\pi kt}{T}\right)\right] + \sum_{k=1}^{\infty}\left[A2_k \sin\left(\frac{2\pi kt}{T}\right)\right] \tag{3.5}$$

Figure 3.9 shows an example of a periodic signal decomposed in two elementary sine functions.

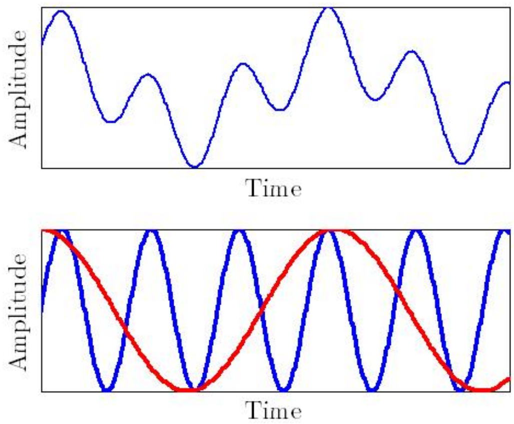

Figure 3.9: Illustration of signal decomposition

The frequency $f_0 = \frac{1}{T}$ is the **fundamental frequency** of $s(t)$. The other higher frequencies are given by $f_k = \frac{k}{T} : \infty \geq k \geq 2$. The signals with these frequencies are called **harmonics** of $s(t)$.
The Fourier **coefficients** (A_0, $A1_k$, $A2_k$) depend on the signal's waveform. Because frequency is linked to index k, the coefficients implicitly depend on frequency.
Once more we can use the Euler's theorem to express the equation (3.5) in the complex plane. Then we get:

$$s(t) = Re\left[\sum_{k=-\infty}^{+\infty} A_k e^{j2\pi\frac{k}{T}}\right]$$

Let us focus on the result of Fourier transform that gives the coefficients of the exponential harmonics expression:

$$A_0 = \frac{1}{T}\int_0^T s(t)$$

$$\forall k : 1 \geq k > \infty, \quad A_k = \frac{1}{T}\int_0^T s(t)e^{j\frac{2\pi k}{T}t}dt$$

Finally, the Fourier series decomposition gives a set of couples $\{frequency, amplitude\} = \{f_k, A_k\}$. Then the **power frequency spectrum** is given by the graph:

$$P_s : f_k \rightarrow |A_k|^2$$

A subtle, but very important, aspect of the Fourier spectrum is its uniqueness: you can unambiguously find the spectrum from the signal (decomposition) and the signal from the spectrum (composition).Thus, any aspect of the signal can be found from the spectrum and vice versa. A periodic signal can be defined either in the time domain (as a function) or in the frequency domain (as a spectrum). **Fourier transformation** extends this notion to non-periodic signals. So, each signal can be expressed in time or frequency domain.

Spectrum of pulse train

To fix the reader's ideas, let us try to get the power spectrum of a well-known periodic signal: the rectangular pulse train, illustrated on Figure 3.10. Let us consider a pulse train signal $s_p(t)$, with pulse amplitude A, pulse width L, and period T.

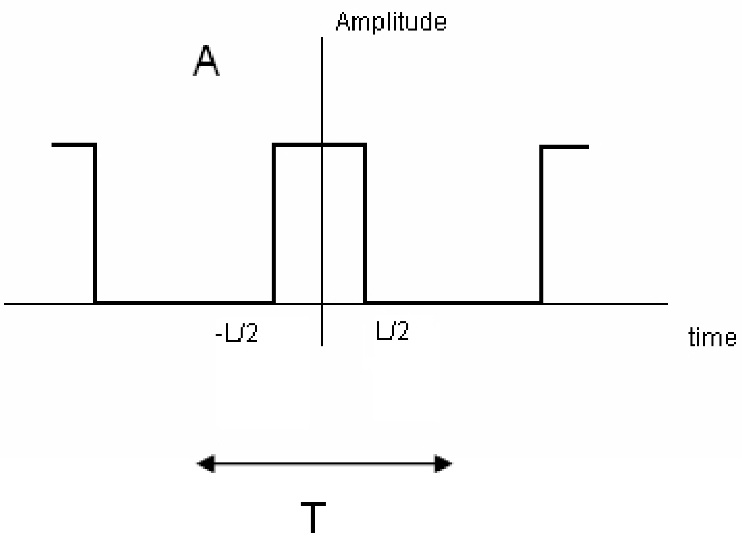

Figure 3.10: Pulse train periodic signal

In order to plot the spectrum, we compute the coefficients A_k, we get:

$$A_k = \frac{1}{T} AL \frac{\sin(2\pi kt/T)}{(2\pi kt/T)}$$

This expression has the form $\frac{\sin(x)}{x}$ that has a maximum value of unity at $x = 0$ and approaches 0 as x approaches infinity, oscillating through positive and negative values (Figure 3.11). Therefore P_s has a maximum value of AL/T at $f = 0$. It is defined as: $\forall 1 \leq k < \infty; P_s(\frac{k}{L}) = 0$.

3.2 Digital modulation

Digital modulation is the process by which a digital information source is transformed into waveforms that are compatible with the characteristics of the channel. We can consider two kinds of digital modulation:

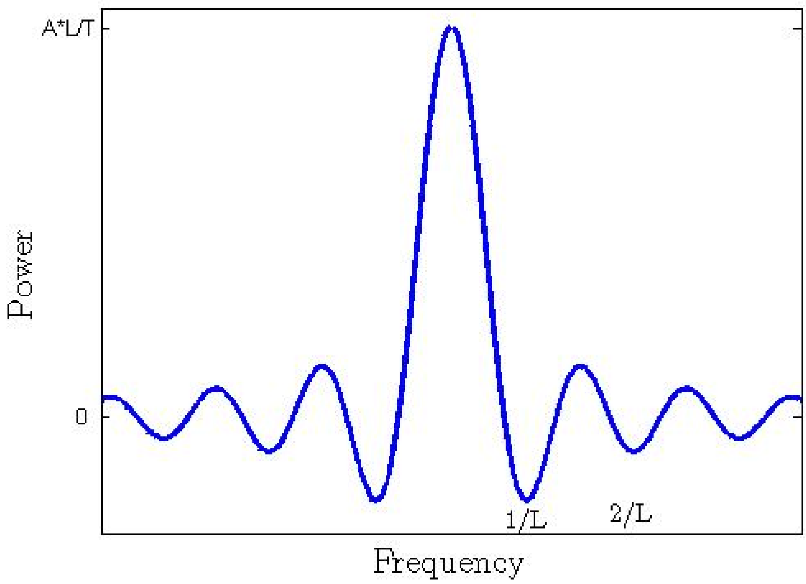

Figure 3.11: Power Spectrum of a pulse train periodic signal

1. The **baseband modulation** consists in creating digital pulses (having a center frequency around $0Hz$) corresponding to data bits to be transmitted.
2. The **bandpass modulation** is the process by which an information signal is transformed into a sinusoidal waveform. Since a sinusoid has three features : amplitude, phase and frequency, bandpass modulation can be defined as the process by which the amplitude, phase, frequency of an RF carrier, or a combination of them, is varied in accordance with the digital information signal to be transmitted.

3.2.1 Modulation techniques

Roughly, there are three ways to modify a signal according to data: by acting on its phase, amplitude or frequency. The table hereunder represents the terminologies for digital and analog modulations:

	Analog	Digital
Frequency	FM (Frequency Modulation)	FSK (Frequency Shift Keying)
Amplitude	AM (Amplitude Modulation)	ASK (Amplitude Shift Keying)
Phase	PM (Phase Modulation)	PSK (Phase Shift Keying)

To avoid misunderstanding, note that before modulation, data is called **bit** and after modulation we get **symbols**. A symbol can carry more than one bit.

3.2.2 Phase Shift keying modulation

The PSK (Phase Shift keying modulation) is the most important and basic modulation in digital communication. As its name indicates, the signal phase ϕ changes according to the data bits:

$$s_x(t) = A\cos(2\pi ft + \phi) = Re\left[Ae^{j\phi}e^{j(2\pi ft)}\right]$$

For this analysis, only the complex envelope will be considered since it is this part that conveys information.

Binary Phase Shift Keying

BPSK(Binary Phase Shift Keying) is the simplest PSK modulation. Binary means there are two possible values for the signal phase 0 or π. So, when a transmitter wants to send a '0' bit, it sends a signal with a phase $\phi = 0$ and when it wants to send a '1' bit, it sends the same signal but with a phase $\phi = \pi$. If we want to send a bit sequence $d[k]$, and we consider only the complex envelop, the signal will be:

$$Z(t) = Ae^{j\phi_k(t)}$$

$$\text{with: } \begin{cases} d[k] = 0 & \Rightarrow & \phi_k(t) = 0 \\ d[k] = 1 & \Rightarrow & \phi_k(t) = \pi \end{cases}$$

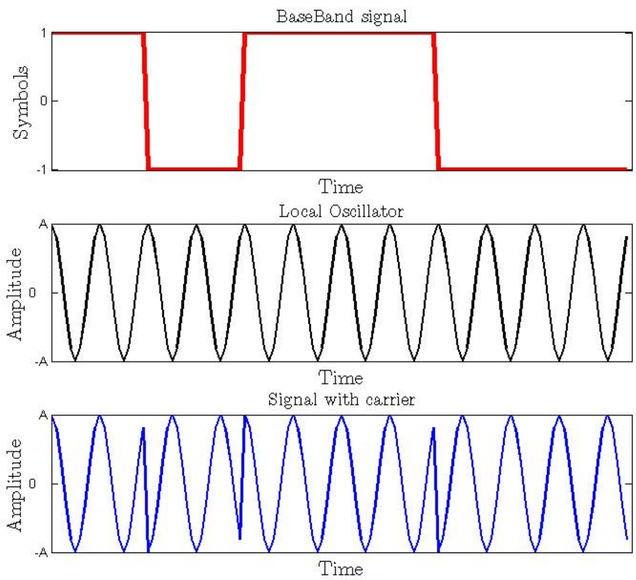

Figure 3.12: BPSK signal modulation of the data sequence [1 0 1 1 0 0]

For example, Figure 3.12 illustrates the BPSK modulation corresponding to the data sequence [1 0 1 1 0 0].

The **constellation diagram** is a convenient way to visualize the modulation symbols in the complex plane. This diagram is the visualization of modulation alphabet on the unit circle in the complex plane. Figure 3.13 shows the BPSK alphabet. Note that the phase values are real but it is obviously not always the case.

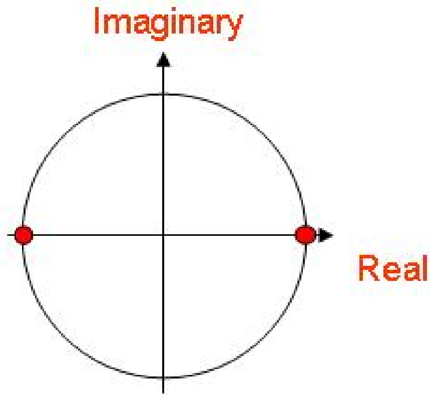

Figure 3.13: BPSK Constellation

M-ary Phase Shift Keying

A BPSK-modulated symbol has 2 states 0 or π. So it can convey only one bit data (1 or 0). But it could be possible to let a symbol convey several bits. For that, it must have 2^M states, where M is the number of bits transmitted by one symbol. In other words, it is needed to increase the number of points on the constellation. Typically, Figure 3.14 presents a 4-ary PSK's constellation, also known as QPSK.

The dilemma for M-ary PSK

Naturally, we want to put as many data bits on a symbol as possible. But, to increase the number of data bits conveyed by a symbol, more points on the constellation are necessary. However, the more numerous the signal points are, the shorter are the intervals between them on the unit circle. On the other hand, we know that the medium is noisy. What means that the receiver does not receive exactly the transmitted signal. Therefore, during the demodulation process, the closer the points on the constellation are, the more mistakes the receiver can make.
In a nutshell, although M-ary PSK is more efficient, it suffers from the lack of sufficient intervals.

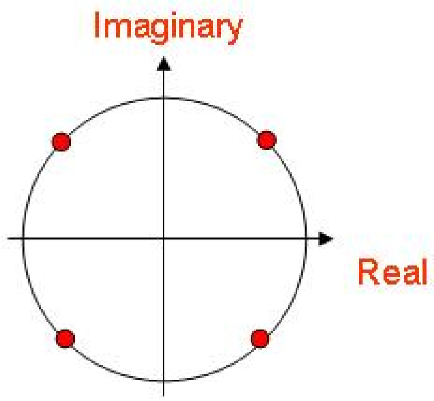

Figure 3.14: QPSK constellation

3.2.3 Important indexes

To analyze the performance of a transmission, it is convenient to have standardized indicators. This section presents the main ones.

BER (Bit error rate)

The bit error rate (BER) is the ratio of the number of **bits** misrecognized to the total number of **bits** transmitted during a specified time interval.

BER =number of misrecognized **bits** / total number of transmitted **bits**

The smaller BER, the better the efficiency of transmission.

SNR (Signal to noise ratio)

"Signal-to-noise ratio" is an engineering term for the power ratio between a signal (meaningful information) and the background noise. For convenient reasons, it's expressed in dB:

$$\boxed{SNR = 10\log_{10}\left(\frac{P_s}{P_n}\right) \qquad [dB]}$$

where $P_S(Watts)$ is the power of the received signal and $P_N(Watts)$ is the power of the background noise.

In this study, the **additive white Gaussian noise** (AWGN) has been chosen to model the channel. AWGN is the linear addition of **white noise** (i.e., the power spectral density of noise has equal power in any band, at any frequency) to the useful signal. The term **Gaussian distribution** means that the noise amplitude function follows a Gaussian distribution.
The model does not account for the phenomena of fading, frequency selectivity, interference, nonlinearity or dispersion. However, it produces simple, tractable mathematical models which are useful for gaining insight in the underlying behavior of a system before these other phenomena are considered. AWGN comes from many sources, such as the thermal vibration of atoms in antenna amplifiers, radiation coming from electrical devices, etc.

SNR is a very important index for communication systems. It measures the relative quality of the signal. The greater the ratio, the easier it is to identify and subsequently isolate and eliminate the source of noise.

BER derivation

It is interesting to express the quality of a communication system (BER) in function of the signal quality (SNR) and the modulation used.
Typically, for BPSK modulation and a SNR equal to $0.5[dB]$, if the transmitter sends 10,000 times the symbol 1 (represented by a single big point on the left part of Figure 3.15), the receiver will receive a scatter of symbols (depicted on the right part of Figure 3.15) because of the noise.

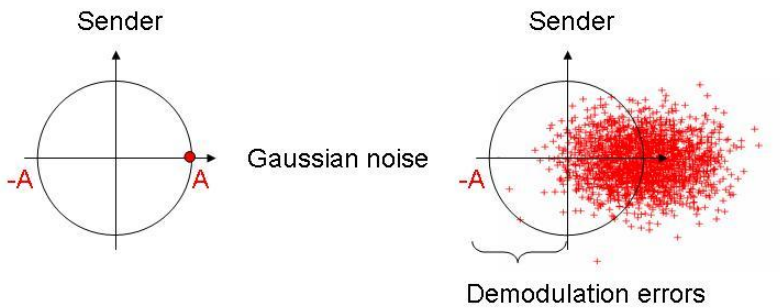

Figure 3.15: Symbols received with an AWGN channel

The BPSK demodulation is performed by comparing the sign of the received symbol. If it is positive then a bit 1 will be detected else a bit 0. Therefore in the above case, all negative symbols are demodulation errors. In Figure 3.16, the probability density function of the amplitude of received signals represents this fact. The darkened area shows the probability that a demodulation error occur.

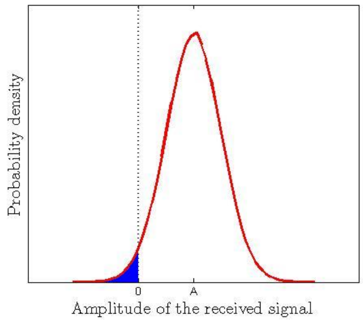

Figure 3.16: Probability density function of symbols received with an AWGN channel

Mathematically, the demodulation error probability for BPSK is given by the cumulative distribution function of the normal distribution with mean A and variance σ^2:

$$\begin{aligned} P_e &= P(s<0) = \tfrac{1}{\sqrt{2\pi\sigma}} \int_{-\infty}^{0} \exp\left(\tfrac{(x-A)^2}{2\sigma^2}\right) dx \\ &= \tfrac{1}{2}\mathrm{erfc}(\sqrt{\gamma}) \end{aligned}$$

where

$$\gamma = \frac{A^2}{2\sigma^2} = \mathrm{SNR}$$

and

$$\mathrm{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} \exp(-u^2) du$$

Figure 3.17 plots the BER according to the SNR. It is generally assumed that above BER $= 10^{-4}$, the received signal cannot be recovered. The corresponding SNR $\simeq 8.5$ dB is called the **demodulation threshold**. In the same way, below SNR $\simeq 3$ dB, the signal intensity is too weak and cannot be detected with an antenna. For BPSK modulation, this value is called the **detection threshold**.

3.3 Adaptive Array Antenna formulation

Let us remind the fundamental principle of AAA. An AAA is a network of weightable element antennas. By changing the amplitude and phase of incoming signal at each antenna, the DSP controls electronically the AAA directivity in order to maximize the output for a desired signal. So, the AAA acts as a spatial filter generating high sensitivity towards the direction of the desired signals and, in contrary, the sensitivity is reduced for the direction of jammers.

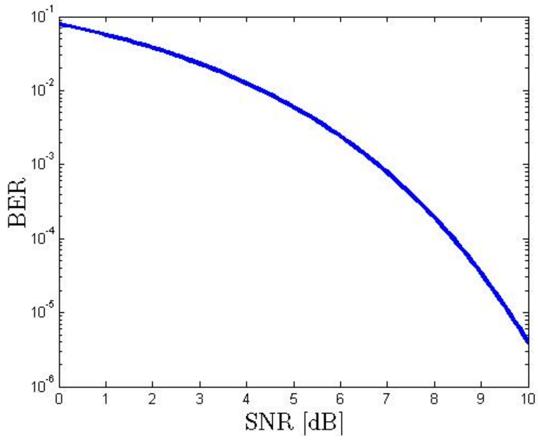

Figure 3.17: BER derivation

In this study, each node has an AAA. When the mobile transmits a frame, only one element antenna is used. In this way, the antenna responds like an omni-directional antenna during the transmission process. In reception, all element antennas are used, enabling the AAA to maximize the received signal.

3.3.1 Input and output expression

Steering vector

Because each element antenna is separated from the transmitter by a different distance (depending on its position) and due to the propagation delay, the incident signal at each element antenna has a different phase.

Since the wavelength λ is known as well as the distance between pairs of antenna, it is easy to evaluate the phase difference between each pair of antennas.

Let us use Figure 3.18 to assess the distance difference between the two first antennas and the transmitter 'Tx'.

Let us make the common assumption of plane-waves: "the transmitter is sufficiently far away from the receiver such that the Direction of Arrival (DoA) of wave is the same at all element antennas". So, the wave has to cover the distance 'a' and 'a'+'c' to reach the antenna number 0 and 1 respectively. By geometrical observation, 'c' is derived as follows:

$$c = d\cos\left(\frac{\pi}{2} - \theta\right) = d\sin(\theta)$$

where θ expressed in radians is the arrival angle of the signal.

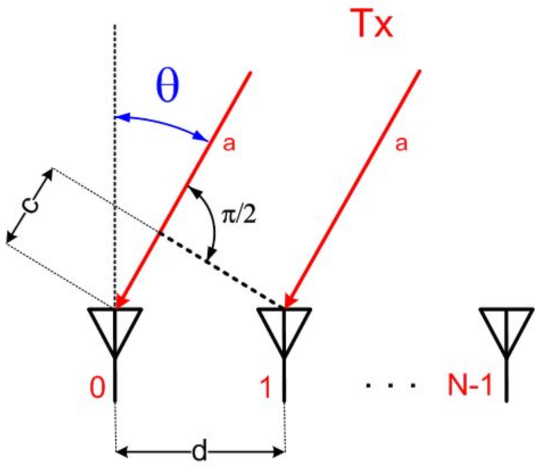

Figure 3.18: Geometrical observation of array antenna

Moreover, the wave phase shift due to the distance to cover x is given by:

$$\phi_{diff} = \frac{2\pi}{\lambda} x$$

Consequently, by replacing x with the c expression, we get the phase difference of antenna 0 by comparison with antenna 1:

$$\phi_{diff} = \frac{2\pi}{\lambda} d \sin(\theta)$$

Or, because we focus on the phase difference of antenna 2 with respect to 1:

$$\phi_{(1)} = -\frac{2\pi}{\lambda} d \sin(\theta)$$

Roughly, for the DoA θ the phase differences among the element antennas of a uniform linear array will be:

$$\forall \quad 0 \leq n \leq N-1 : \quad \phi_{(n)} = -\frac{2\pi}{\lambda} (nd) \sin(\theta)$$

The phase differences can be expressed in the complex plane. Indeed, the **Steering vector** represents the phase differences vector among the element antennas according to the signal DoA (Figure 3.19). Mathematically, considering N element antennas and a DoA $= \theta$, the steering vector of a circular array is expressed as:

$$A(\theta) = \begin{pmatrix} e^{j\phi_0} \\ e^{j\phi_1} \\ \vdots \\ e^{j\phi_{N-1}} \end{pmatrix} = \begin{pmatrix} 1 \\ e^{-j\frac{2\pi d}{\lambda}\sin(\theta)} \\ \vdots \\ e^{-j(N-1)\frac{2\pi d}{\lambda}\sin(\theta)} \end{pmatrix}$$

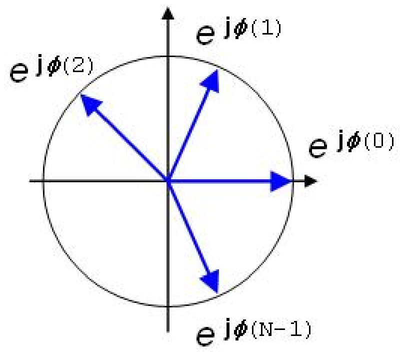

Figure 3.19: Example of steering vector

The above model considers that element antennas are placed along a line. However, in an ad hoc network, the receiver does not know, a priori, where the next hop is towards the node it is speaking to. So, in many mobile communication applications, circular arrays are more suitable (Figure 3.20).

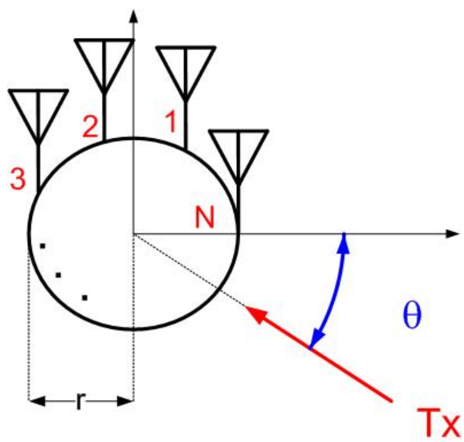

Figure 3.20: Geometrical observation of circular array antenna

In the same way, by geometrical observations, the steering vector will be:

$$a(\theta) = \exp\left\{j\left(\frac{2\pi}{\lambda}\right) r \sin\left(\frac{\pi}{2}\right) \cos\left[\theta - \left(2\left(\frac{\pi}{N}\right)(k)\right)\right]\right\}';$$

where 'r' is the radius of the circle and $k : 0 \leq k \leq N-1$ is the antenna number.

Input of AAA

Due to the steering vector formulation, it is possible to define the input of AAA. Let us remember that AWGN has been chosen to model the channel noise. Note that the noise components ($n(t)$, where $1 \leq t \leq$ number of symbols transmitted) are uncorrelated each other. Therefore, if the transmitted signal is $s(t)$(analytic expression), the input of an AAA composed of N elements antennas has the form:

$$X(t) = s(t)A(\theta) + N(t)$$

$$\begin{pmatrix} x_0(t) \\ x_1(t) \\ \vdots \\ x_{N-1}(t) \end{pmatrix} = s(t) \begin{pmatrix} e^{j\phi_0} \\ e^{j\phi_1} \\ \vdots \\ e^{j\phi_{N-1}} \end{pmatrix} + \begin{pmatrix} n_0(t) \\ n_1(t) \\ \vdots \\ n_{N-1}(t) \end{pmatrix}$$

Output of AAA

Each element antenna is weighted with a complex weight $w(k)$ where $0 \leq k \leq N-1$. In addition, the output of AAA is the sum of each element antenna:

$$Y(t) = \sum_{k=0}^{N-1} w_k x_k(t) = (w_0 w_1 \dots w_{N-1}) \begin{pmatrix} x_0(t) \\ x_1(t) \\ \vdots \\ x_{N-1}(t) \end{pmatrix}$$

$$\Leftrightarrow Y(t) = W^H X(t)$$

The weight vector is usually expressed like w^H where ^{H} is the complex transpose conjugate operator.

By changing the weight vector, the AAA sensitivity can be adapted according to the DoA of desired and jammers signals. The end of this chapter aims to examine the algorithms which enable to compute the optimal weights.

3.3.2 Theory of optimal weights

The theory of optimal weights aims at maximizing the output power of AAA by changing the weight affected to each element antenna in function of the AAA input.

Steering vector solution

Let us think about the vector expression of the received signal. The vectors of the received signal are looking at different directions according to the steering vector. Their composition is not optimal as shown on Figure 3.21.

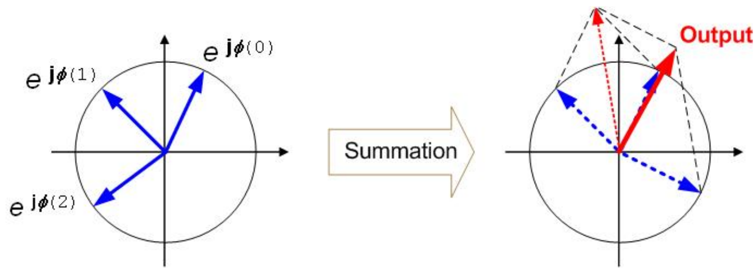

Figure 3.21: Summation of originally signals from each antennas

The solution would be to align the phases of all vectors. It is precisely what could make the weights of AAA. Figures 3.22 depicts this ideal situation.

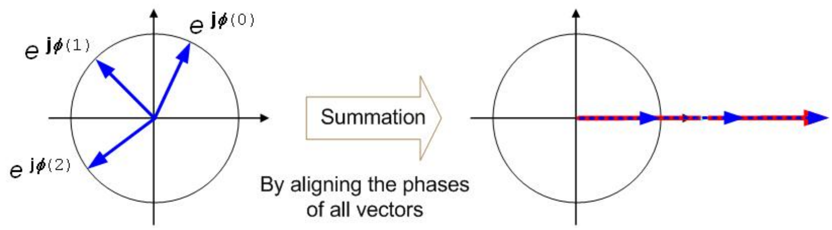

Figure 3.22: Summation of identical phase signals

When the steering vector is used as weight vector, we get

$$\begin{aligned} Y(t) &= W^H X(t) \\ &= A^H(\theta) X(t) \\ &= A^H(\theta) \left[s(t) A(\theta) + N(t) \right] \\ &= s(t) A^H(\theta) A(\theta) + A^H(\theta) N(t) \end{aligned}$$

Let us focus on the part $A^H(\theta)A(\theta)$:

$$A^H(\theta)A(\theta) = \sum_{k=0}^{N-1} e^{-j\phi_k} e^{j\phi_k} = \sum_{k=0}^{N-1} e^0 = \mathrm{N}$$

So the amplitude of incoming signal is multiplied by the number of antennas:

$$Y(t) \quad = \quad s(t)\mathrm{N} + A^H(\theta)N(t)$$

Unfortunately, this solution needs the DoA of incoming desired signal to be known in order to compute the steering vector and, in addition, it considers only a single incident signal. Such assumptions are unrealistic in practical communication.

Wiener solution

In practice, AAA have to deal simultaneously with desired signal and jammer signals for which it does not know the DoAs. Moreover, how to know before communication if the signal is desired?

The Wiener solution addresses those issues by using the Minimum Mean Squared Error (MMSE) algorithm and a **reference** signal known by the nodes that want to communicate with each other.

The reference signal is a 'pure' signal without any disturbance of interference or noise. It is included in the beginning of each transmitted frame. In digital communication systems, such a known sequence so called **preamble** is inserted in each frame for various purposes, e.g., for synchronization.

Let us remove the steering vector solution assumptions and consider a situation including one desired signal $s_D(t)$ having the right preamble and one interference signal $s_I(t)$. The AAA input shall be:

$$X(t) = s_D(t)A(\theta_D) + s_I(t)A(\theta_I) + N(t)$$

where θ_D is the DoA of the desired signal and θ_I is the DoA of the jammer signal.

The ideal process should be to make all phases of desired signal vectors identical while those of interference vectors are changed so as to cancel each other. For a 4-element AAA, Figure 3.23 depicts this ideal situation where continuous line vectors represent the desired signal and the dotted line vectors the interfering signal.

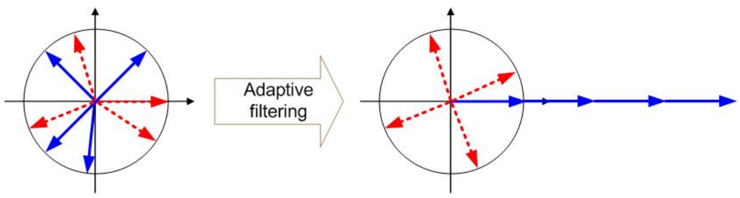

Figure 3.23: Summation of desired signals and cancellation of interferers

By this process, AAA acts like an adaptive filter that outputs only the desired signal from an input composed of desired signal plus interference plus noise. With this intention, by changing weight vectors, MMSE aims to minimize the difference between antenna output and the reference.

Mathematically, the problem statement depicted above, can be expressed as:

find $w_j^* : 0 \leq k \leq N-1$ so that:

$$\begin{aligned}
\sum_{k=0}^{N} w_k^* x_k(0) &= s_D(0) \\
\sum_{k=0}^{N} w_k^* x_k(1) &= s_D(1) \\
\vdots &= \vdots \\
\sum_{k=0}^{N} w_k^* x_k(P) &= s_D(K)
\end{aligned} \tag{3.6}$$

where P is the length of preamble.
Let us rewrite the equations in a matrix expression:

$$\begin{pmatrix} w_0^* & \cdots & w_N - 1^* \end{pmatrix} \begin{pmatrix} x_0(0) & \cdots & x_0(P) \\ \vdots & \ddots & \vdots \\ x_N - 1(0) & \cdots & x_N - 1(P) \end{pmatrix} = \begin{pmatrix} s_D(0) & \cdots & s_D(P) \end{pmatrix}$$

$$\Leftrightarrow w^* X = r$$

where r is the reference line vector. In practice, the number of antennas is really quite lower than the length of preamble. Therefore, it is not possible to determine precisely the weights that comply with all equations perfectly. However, by multiplying both sides of the previous equation by X^H:

$$\begin{aligned}
w^* X X^H &= r X^H \\
w^* &= (X X^H)^{-1} r X^H
\end{aligned}$$

The square matrix (XX^H) so called **correlation matrix** is a key figure in digital signal processing. By rewriting it as $R_{xx} = \mathcal{E}(XX^H)$ where $\mathcal{E}$ is the expected value operator (mean),

$$w^* \simeq R_{xx}^{-1} r X^H$$

Note that the correlation matrix is Hermitian ($R_{xx} = (R_{xx}*)^t = R_{xx}^H$) and positive definite. On the main diagonal, the correlation matrix contains the average channel powers of the elements antenna and the off-diagonal elements specify the complex correlation values between all pairs of elements antenna [Aut04]. The inverse of R_{xx} exists due to the uncorrelated noise included in X. In other words, thanks to the Gaussian noise, vectors of X are linearly independent in such way that the inverse of the correlation matrix exists.

In this way, the number of equations is reduced to the number of element antennas. So, the Wiener solution does not provide the perfect weights but those that can output the best output matching with the desired signal. It is understandable that Wiener solution cancels possible interfering signals since the weights are chosen to produce the desired output (i.e. preamble) according to the input $x(t)$ which contains both desired and jammer signal.

Thanks to the Wiener solution used to set the weights, the receiver does not need to know the position, i.e, DoA of the transmitter and, in addition, it responds as a spatial filter. Unfortunately, before a node can engage a communication with another one, it has to know the right preamble. Consequently, it is needed to define a preamble distribution policy.

For example, we can imagine a DHCP-like protocol in which some dedicated terminal would distribute the preamble corresponding to the network. However, this approach constitutes a single point of failure. Moreover, if only one preamble is used through the whole network, it will be impossible to distinguish a desired signal from a jammer one within the same network. Another option would be to include a “preamble request” in the RREQ packet. So, when the RREQ reaches the first next hop, this last one decides to accept the communication by sending back a “preamble reply” packet that includes a specific preamble. This issue has not been developed here and could be the subject of future work

Besides, due to preamble, the communication bit rate is quite reduced.

Eigenvalue decomposition solution

An eigenvector of a linear application ($T : \mathbb{E} \rightarrow \mathbb{E}$), defined on a vector space $\mathbb{E}$, is a non-null vector whose direction is unchanged by that linear application. In other words, the application can change its direction and norm but can not modify its direction [Thi03]. Mathematically, a vector V is an eigenvector of linear application T if:

$$T(V) = \lambda_V V$$

where λ_V is the eigenvalue (scalar) corresponding to V
Since the linear application T can be fully expressed as a matrix A,

$$AV = \lambda_V V$$

Imagine the ideal scenario where only one signal impinges the AAA from a particular DoA. Then, the correlation matrix is fully correlated since the phase and the amplitude fluctuate together according to fading. By opposition, in a scenario where a large number of signals reach the AAA from every direction, the phase and amplitude relation between each pair of antenna is completely random. As a consequence the correlation matrix is completely uncorrelated.

Natural channels are somewhere between these two extremes. The degree of correlation is provided by the eigenvalues of the correlation matrix. Since R_{xx} is symmetric, the R_{xx} diagonalizing according to the eigenvalue decomposition is given by:

$$R_{xx}V = V\Lambda \qquad R \in \left(\mathbb{I}^N * \mathbb{I}^N\right)$$

where,

$$V = (v_1 v_2 \cdots v_N) \text{ and } \Lambda = \begin{pmatrix} \lambda_1 & 0 & \cdots & 0 \\ 0 & \lambda_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \lambda_N \end{pmatrix}$$

Multiply both left-hand side by V^H

$$V^H R_{xx} V = \Lambda V^H V$$

Since R_{xx} is Hermitian, its eigenvectors are orthogonal: $\forall 1 \leq l, m \leq N, \quad v_l^H v_m = 1$ if $l = m$ else 0[Thi03],

$$V^H R_{xx} V = \Lambda V^H I$$
$$V^H R_{xx} V = \Lambda V^H$$

For the k-th eigenvalue and corresponding eigenvector:

$$v_k^H R_{xx} v_k = \lambda_k$$

$$v_k^H \mathcal{E}(xx^H) v_k = \lambda_k$$
$$\mathcal{E}(v_k^H x x^H v_k) = \lambda_k$$
$$\mathcal{E}\left(|v_k^H x|^2\right) = \lambda_k = P_{x,out}$$

It means that the eigenvalue λ_k is equal to the output power of the AAA in which the corresponding eigenvector v_k is employed as weight vector.

Due to the orthogonality among eigenvectors, a peak on the antenna pattern obtained by an eigenvector is overlapped with a null obtained by other eigenvectors. Radiation patterns of a 4-element AAA resulting from eigenvectors weights are plotted on Figure 3.24.

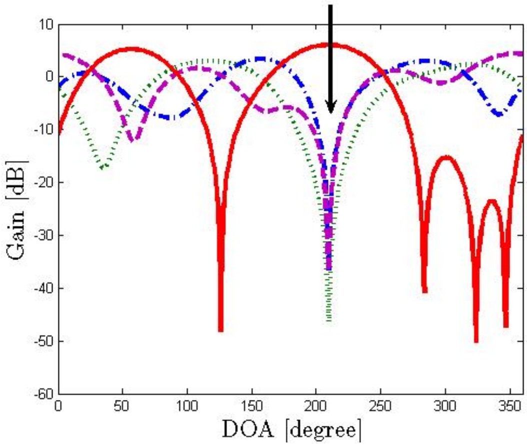

Figure 3.24: Using eigenvectors as weight with one incoming signal

Consequently, to maximize the AAA output power for the incoming signal, the eigenvector corresponding to the highest eigenvalue has to be chosen as AAA weighs.

This technique works very well if there is only one incoming signal. In addition, it does not require any reference in frames. However, with more than two signals, it depends on the power relation between the signals. Indeed, since the signal separation results from power difference, equal power signals cannot be isolated. Obviously, if signals do not have the same power, they can be separated. Figure 3.25 illustrates those two scenarii for two incoming signals with different power and equal power respectively.

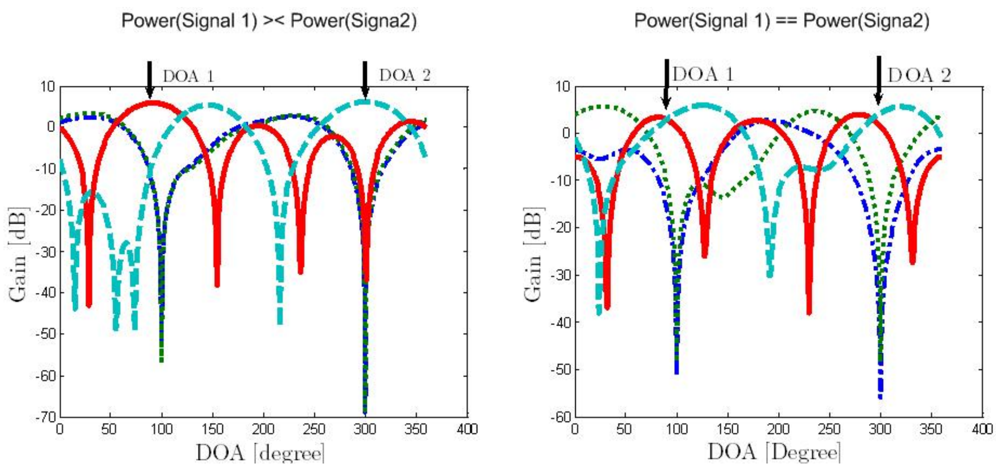

Figure 3.25: Using eigenvectors as weight with two incoming signals

3.3.3 AAA under Rayleigh fading

Input of AAA

The previously established input of AAA considers only one direct line of sight signal (θ).

$$X(t) = s(t)A(\theta) + N(t)$$

However, this is without considering multiple reflected signals generated along the path between transmitter and receiver. To take this phenomenon into consideration, the input of each element antenna is the composition of several replicated signals. Figure 3.26 shows five replicated signals that reach the receiver with different DoAs.

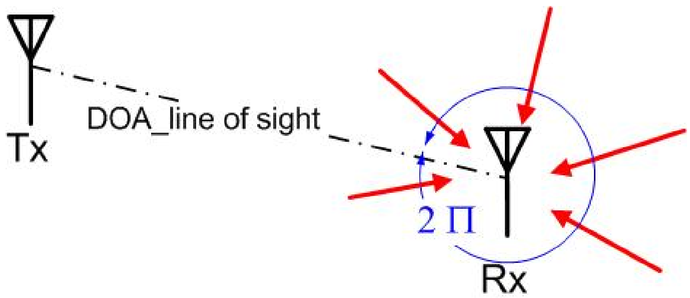

Figure 3.26: Several replicated signals reach the receiver

To formulate a Rayleigh fading channel, we suppose that:

- There are M delayed versions of the signal at the receiver that have all the same amplitude:
$$s_m : \forall 1 \leq m \leq M, |s_m| = \frac{\sqrt{P_s}}{M}$$
where P_s is the signal power at the receiver.
- The DoA of M scattered signals ($DoA_m : 1 \leq m \leq M$) are randomly chosen between 0 and 2π according to a uniform distribution. Therefore, the steering vector a has to be computed for each ray.
- Since each replicated signal takes a different path from the transmitter to the receiver, they cover a different distance as well. So, they arrive at the receiver with a phase shift ($\phi_m : 1 \leq m \leq M$). A uniform distribution between 0 and 2π has also been chosen to simulate the phase shift.

So, the input of AAA within a Rayleigh fading channel is:

$$X(t) = \sum_{m=1}^{M} A(DoA_m)s_m(t)e^{j\phi_m} + N(t)$$

Theoretically, the amplitude of received signal, i.e, at the input of AAA, will follow a Rayleigh distribution like the dotted line depicted on Figure 3.27. The arrow on this figure shows the amplitude of received signal without Rayleigh fading consideration. So, it means that the Rayleigh fading has only a bad influence on the quality of the received signal. In other words, the probability to have a better signal than expected without Rayleigh fading is null.

Output of AAA

Since an omni-directional antenna produces a theoretic gain about $0dB$, its output is the same as its input. So, in a Rayleigh fading environment, the output amplitude follows a Rayleigh distribution

$$f(x,\sigma) = \frac{xexp^{\left(\frac{-x^2}{2\sigma^2}\right)}}{\sigma^2}$$

On the other hand, the AAA produces a certain gain depending on the AAA parameters and the position of the receiver and the transmitter. According to theory, the AAA output for a desired signal (with a Rayleigh amplitude distribution input) is an Gaussian distribution (Figure 3.27).

$$f(x,\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}}exp\left(-\frac{(x-\mu)^2}{2\mu^2}\right)$$

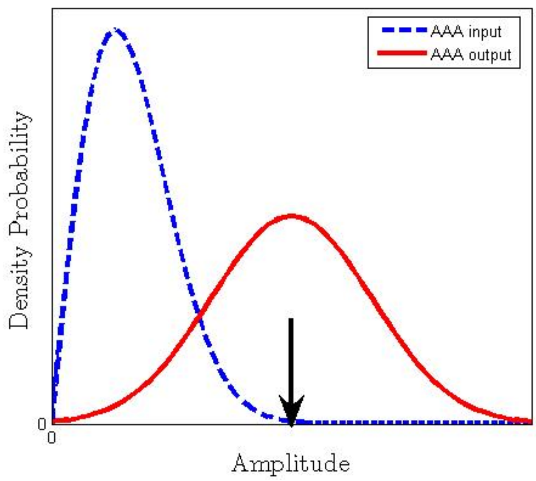

Figure 3.27: AAA input and output under Rayleigh fading channel

Chapter 4

Computer simulations

In the previous chapters, the theoretical concepts of adaptive array antenna, fading and AODV routing protocol have been described. These notions have then been formalized in mathematical terms.

Now, the computer simulations will be detailed in order to emphasize the potential of AAA in a life-sized ad hoc network environment. Before starting, it could be interesting to remind and synthesize the project objectives:

1. Study the consequences of fading from the network layer perspective.
2. Show to what extent fading degrades signal quality and highlight the AAA ability to mitigate the fading phenomenon.
3. Couple AAA technology with ad hoc wireless environment and highlight the benefits from the network layer perspective in terms of hop count and delay.

To reach these objectives, simulations have been set-up. The following list briefly summarizes the components that have been implemented.

Adaptive Array Antenna A fully worked and realistic physical layer (PHY) with AAA technologies and fading consideration

AODV A simplified version of AODV routing protocol in order to provide a multi-hop network environment

CSMA/CA An hybrid MAC protocol inspired from CSMA/CA and slotted ALOHA.

4.1 Methodology

In this section, the general structure of the project is described. More precisely, this section clarifies the methodology used to develop the simulations and to meet the previously defined requirements. Figure 4.1 is a data flow chart showing the data exchanges (arrows) between the main process entities (rectangles) of the simulation.

The next subsections clarify the processes from Network, Data link and Physical layer perspectives.

4.1.1 Network layer

The reasons for choosing the AODV routing protocol have been detailed in the chapter 2. A simplified version of AODV has then been implemented. Below are listed all the assumptions and used simplifications:

- The process called "*Ad hoc Environment Generator*" generates randomly the position of the nodes and computes the distance and the angle between each pair.
- Nodes are static and do not fail.
- To perform the RREQ flooding, the simulation needs to know which are the direct neighbors of each node. For this purpose, a binary connection matrix specified as follow has been used: Connection$(i, j) = 1 \Rightarrow$ there is a connection from node i to node j, *else* there is none.
  Although this representation is simple, it does not match with the reality of a wireless network because the link state is determined by the SNR of the receiver. For this reason, this matrix has been avoided and the SNR output provided by the physical layer of the receiver has been used instead. Therefore, when a node send a RREQ, this one is received by every other node having a SNR output sufficiently high (modulation threshold).
- Because the nodes are neither mobile nor susceptible to fail, the RERR message has not been implemented.
- Message RREP is not implemented neither. To compute the route hop count, we use the RREQ message hop count when it reached the destination.

Those limitations need some more explanations. MatLab has been chosen to implement all the features because it is a high-level technical computing language that provides many useful processor-optimized libraries. Specifically, it supports the matrix operations and data visualization tools that are fundamental to physical layer engineering. Unfortunately,

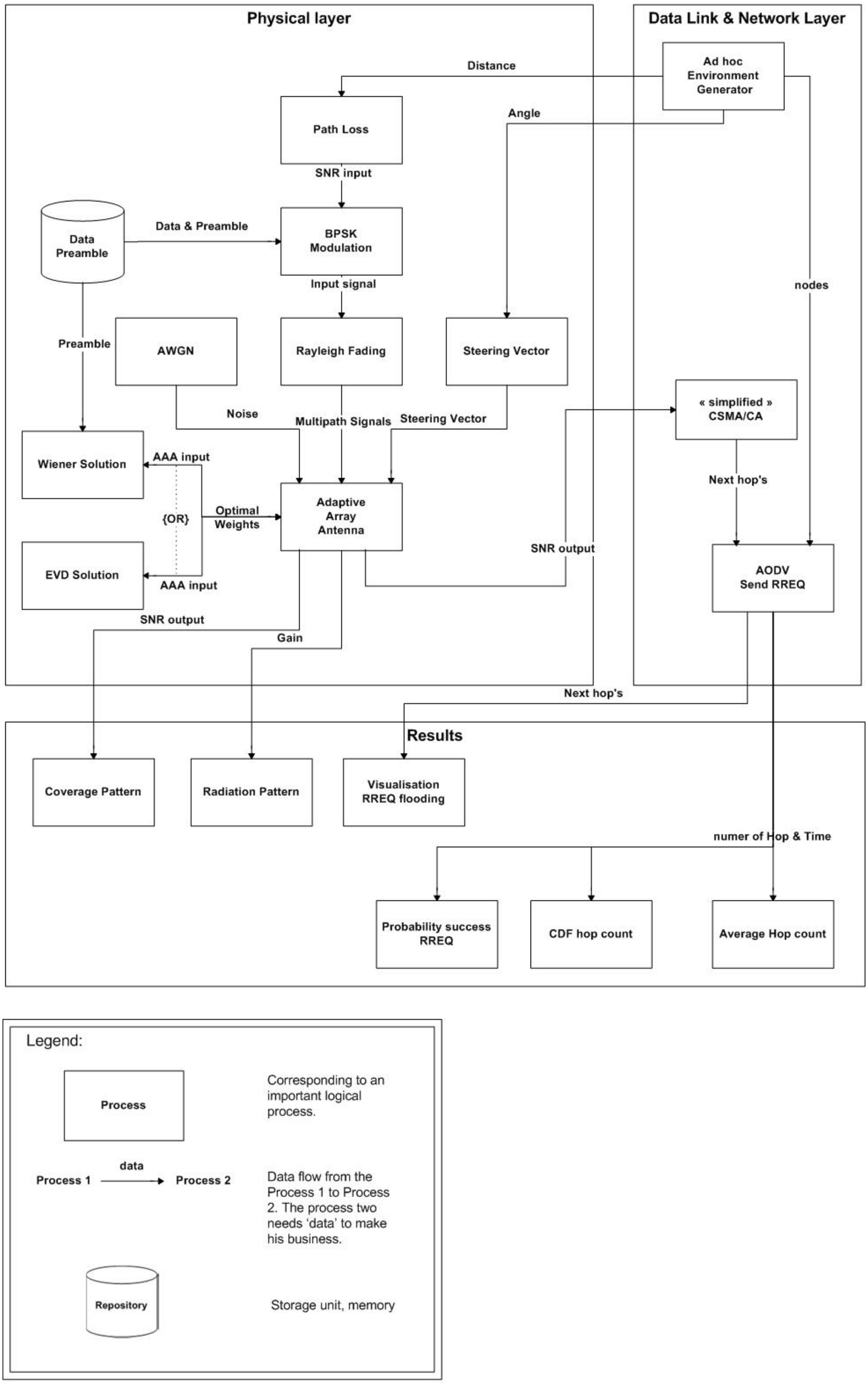

Figure 4.1: Structure of the project

MatLab is not very suitable neither for the network layer simulations nor for the routing table implementation. Therefore, the improvement of the network layer could be the subject of a future work.

4.1.2 Data-link layer

The Data-link layer defines how and when a node is allowed to access the communication medium.
Because an antenna can only transmit or receive and never do both at the same time, a terminal cannot detect eventual collisions. In other words, when a node transmits a frame, it cannot know whether the frame has been corrupted because of a collision. Therefore, the standard *CSMA/CD* cannot be used and the simulation has to consider and avoid the two following problems:

Exposed terminal On Figure 4.2, the nodes ‘B’ and ‘C’ want to send a RREQ to ‘A’ and ‘D’ respectively. In a traditional wire network, they can emit in parallel without collision. But in a wireless network, the node ‘B’ is exposed to ‘C’ transmission and vice versa. To solve this problem, they have to wait a clear medium and coordinate each other before transmitting the frame.

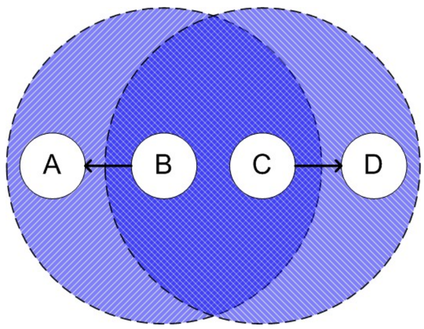

Figure 4.2: Exposed terminal problem

Hidden terminal On Figure 4.3 the nodes ‘A’ and ‘C’ want to send a RREQ to their neighbor ‘B’ but ‘A’ and ‘C’ do not know each other i.e. ‘A’ and ‘C’ are hidden from each other. Then, even if they listen the medium, they do not know they transmit at the same time. Therefore, the node ‘B’ will receive unintelligible messages.

Therefore, our simulation used hybrid simplified version of random access MAC protocol inspired by **CSMA/CA** (Carrier Sense Multiple Access/Collision Avoidance) and **slotted ALOHA** considering a discrete time period and an artificial node synchronization mechanism.

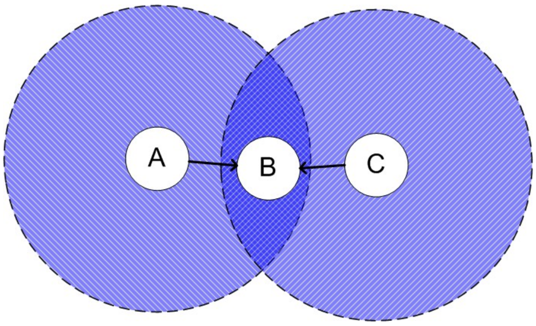

Figure 4.3: Hidden terminal problem

To explain the simplifications that have been done, let us consider the ad hoc topology on Figure 4.4. A link between two nodes means that these are neighbors (there is a bidirectional connection). Below the topology a discrete time diagram is shown, each time slice representing exactly the time needed to send a frame (all use the same size). A node can engage a frame in the medium only when a time slice starts.

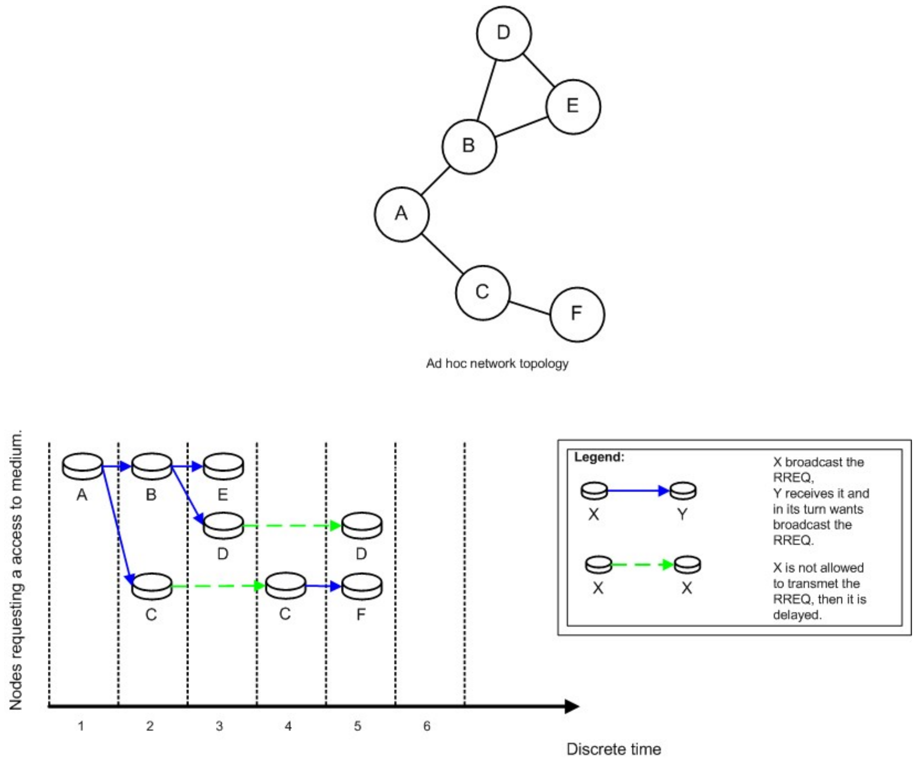

Figure 4.4: Simplified Implementation of CSMA/CA

So, the diagram represents the node requesting the medium according to the time slices. This representation is inspired by slotted ALOHA. However, our MAC protocol "virtually listen to the medium" before engaging a transmission and avoids collisions like

"CSMA/CA". The simulation supervises the sharing of the medium between the network nodes. Actually, whenever 2 or more nodes desire to transmit a frame in the same slot, the simulation decides whether collision will occur or not. If no collision occurs, all the frames are transmitted. In second instance, whenever a collision occurs, the simulation chooses randomly the nodes that can transmit without producing collision, and delays the others ones according to an exponential back-off algorithm.

After the n^{th} collision,
the algorithm chooses the back-off delay randomly from
$\{0, 1, 2, \ldots, 2^m - 1\}$ with $m = min(n, 10)$

To fix the reader's ideas, let us suppose on Figure 4.4 that the node 'A' wants to broadcast a RREQ through the network for the node 'D'. It is the only one requesting the medium for transmission during the first time slice, so it is allowed to broadcast the RREQ to its neighbors, 'B' and 'C'. In turn, 'B' and 'C' have to broadcast the RREQ because they are not the RREQ destination. Nevertheless, 'B' and 'C' cannot send it simultaneously because they have the node 'A' as mutual neighbor (hidden terminal problem). When a conflict occurs, the simulation randomly allows one to transmit and delays the others. In this scenario, the node 'C' is postponed and the node 'B' broadcasts the RREQ to 'E', 'D' and 'A'. Note that since the node 'A' has already sent this RREQ, it will not forward that message once again. So, only nodes 'E' and 'D' request the medium. These two nodes are too close to transmit simultaneously (exposed terminal problem), so the simulation chooses randomly the node 'E' and delays the node 'D'. The process continues until nobody wants to transmit any more. Obviously, two nodes can transmit simultaneously if they are sufficiently far away from the other. Note that due to the back-off mechanism, it is possible that a time slice is not used.

Through this study, we call "simplified version of CSMA/CA" the previously detailed MAC protocol.

In Figure 4.1, the process called "CSMA/CA" needs to know which nodes are the next hop for the broadcasting process. For that purpose, the process "Adaptive Array Antenna" gives it the SNR of the received signal at each node. So, each node for which SNR is greater or equal than the demodulation threshold is considered as neighbor.

4.1.3 Physical layer

A particular emphasis has been placed on the physical layer simulation. To clarify what was made, the following list gives a short explanation of all features which have been implemented.

BPSK Modulation/Demodulation To simulate the Physical layer, the first element to implement is undoubtedly the modulation/demodulation process. The modulation process transforms data called '**bits**' in '**symbols**'. BPSK modulation has been chosen, the use of the well known Euler's theorem for complex numbers, because of its simplicity. Note that the simulation deals with a signal without carrier.

Additive White Gaussian Noise To simulate the noise generated by receiver amplifiers and other electromagnetic radiations added during the transmission, the simulation uses the AWGN.

Free Space Path Loss Energy absorption and magnetic leak of electromagnetic waves in transit between a transmitter and a receiver involve an attenuation of electromagnetic wave.
The Free Space Path Loss is the simplest mathematical model to simulate this attenuation. It assumes there is no obstacle, no gas or anything else on the path from transmitter to receiver [Skl01].

$$Lp = 20 \log_{10} \left(4\pi \frac{d}{\lambda} \right) [dB]$$

where d is the distance from the transmitter and λ is the wavelength. Thanks to the modularity of the simulation, it is easy to modify my program to add another model.

Adaptive Array Antenna All the features necessary to simulate the AAA behavior have been coded. The "steering vector" process gives to the AAA the phase difference between each antenna that is needed to simulate the AAA input. Afterwards, the AAA input is used for the "Wiener solution" or the "EVD solution", which in return provides the optimal weights for each element antenna. In this way, the AAA process is able to compute both output and gain of the adaptive array.

Rayleigh Fading To comply with the reality, the simulation should consider the effect of small-scale fading. With this intention, the Rayleigh Fading has been coded.

The simulation starts with the generation of the ad hoc network environment (nodes positions, creation of the RREQ,...). Distances between nodes enables the "Path Loss" process to compute, for each node, the SNR of received signal. Afterwards, the process "BPSK modulation" creates the received symbols $s(t)$ since it knows the power of received signal. The logical function "Rayleigh Fading" splits these symbols in many multipath signals with a different DoA and phase shift. Those incoming rays combined with steering vector and amplifier noise produce the AAA input $x(t)$. For each transmitted frame, the AAA (of all nodes) computes the optimal weights w_j by using "Wiener Solution" or "EVD Solution" process. The output of the AAA is used by the "CSMA/CA" to determine which node can broadcast the RREQ and which are the next hop in the flooding process.

4.2 Monte-Carlo Simulations

The expression "Monte-Carlo" (MC) method refers to stochastic methods that solve a problem by generating accurate random numbers and observing that fraction of the numbers obeying some property or properties [Wei99]. MC simulations are suitable when the analytic solution either does not exist or is too complicated or require more computation time than the simulation.

Considering many independent instants in time. For each instant, or simulation trial, a scenario is built up by using a different value for random variables. If a sufficient number of simulation trials is considered, then the probability of the expected property occurring can be calculated with a high level of accuracy. In other words, the randomness of simulation is mitigated by the fact of carrying out a great number of simulations.

The three following subsections specify the MC used in this project.

4.2.1 Simulation set-up

The results of simulations depicted in previous sections are characterized by many random parameters:

Position of terminals The position (x, y) of each terminal is randomly chosen from a uniform distribution between 0 and the considered area dimensions.
(x_i, y_i) and (x_j, y_j) are used to compute path loss and the signal direction of arrival between node i and j (assuming line of sight).

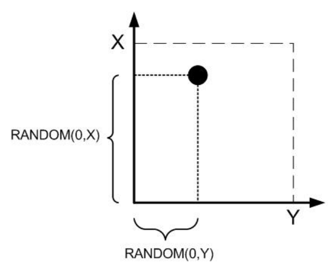

Figure 4.5: Position of terminals

Selection of transmitter and receiver The transmitter and receiver of the simulation trial is randomly uniformly selected among the nodes.

Generation of noise Since the noise model used is AWGN, the noise amplitude follows a Gaussian distribution.

Generation of fading The signal amplitude at the receiver follows a Rayleigh distribution.

4.2.2 MC Output

The expected property is that the transmitted message reaches its destination.

A first kind of metric is the probability that a RREQ reaches its destination. A second one calculates the average number of hops and the average time that a RREQ needs to reach its destination. Finally, a third one considers all scenarii including those where the RREQ does not reach its destination, and organizes hop count and time in a cumulative distribution function.

4.2.3 Confidence intervals

The purpose is to know how many simulations should be performed to get statistically sufficient results?

Let us consider the random variable "RREQ reaches its destination" noted $X(\omega)$ where ω is a topology configuration chosen according to the previously defined parameters.

We want to know what the probability is that *the RREQ reaches its destination*. This probability is noted as p. In order to estimate p, the unbiased and consistent average $\widehat{p}$ (over all simulations performed) estimator has been chosen [Noi03].

The average estimator $\widehat{p}$ gives only a plausible value of p but does not provide any information about the limits of this estimation. That is why it would be interesting to define a "confidence interval" for m.

Since the number of performed simulation (n) is large, according to the "Central Limit Theorem", the distribution of p converges on a normal distribution with an average 'μ'. So, for an normal distribution, the confidence interval is defined as:

$$m - \frac{s}{\sqrt{n}} Q_G\left(1 - \frac{\alpha}{2}\right) \leq \mu \leq m + \frac{s}{\sqrt{n}} Q_G\left(1 - \frac{\alpha}{2}\right)$$

where m and s are respectively the average and the standard deviation of the sample, α is the incertitude coefficient, Q_G is the Gaussian cumulative distribution function.

This formula will be used to prove the accuracy of the simulations.

Chapter 5

Simulation results

In chapter 4 the computer simulations have been specified and the methodology of development has been presented. This section presents the results of the simulations.

5.1 Radiation Pattern

The first enhancement of AAA is certainly its real time capacity to maximize the gain in the direction of the desired signal and to reject the eventually jammer interference. To bring out the AAA behavior, a radiation pattern simulation has been set-up.

Let us examine the results in Figure 5.1. These first four patterns show the evolution of the directivity of one 4-element AAA considering first a terminal at 30° speaking without any interferer (Subfigure 1). Afterwards, one interferer appears and turns around the considered terminal from 120° to 45° (Subfigures 2,3,4). A closer look to the picture could show the peaks and nulls generated by the AAA. However the closer the interferer gets to the desired terminal, the more the gain reduces its last direction.

Figure 5.2 shows what happens in the same scenario when the number of antenna element double, e.g., become eight. Let us focus on the case without interferer, the gain in the direction of the desired signal is larger with the 8-element AAA than with the 4-element antenna. In the same way, this is equally true for the situation with interferer. For instance, compare the fourth radiation pattern (interferer in 45°): it is easily identifiable that the 8-element AAA provides an increased sensitivity to maximize the desired signal and has a better jammer rejection capability. In short, the more antenna elements, the more precise the spatial filter is.

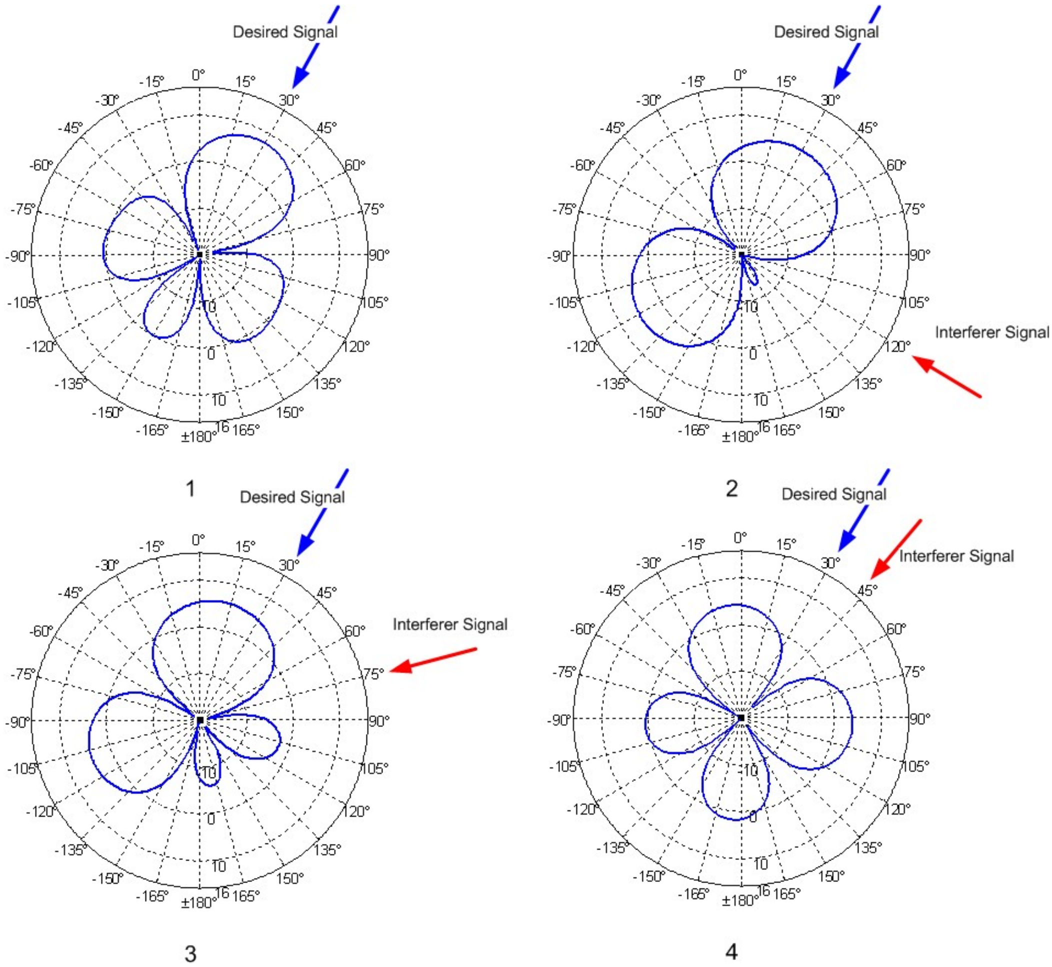

Figure 5.1: Radiation Patterns, 4 element antenna

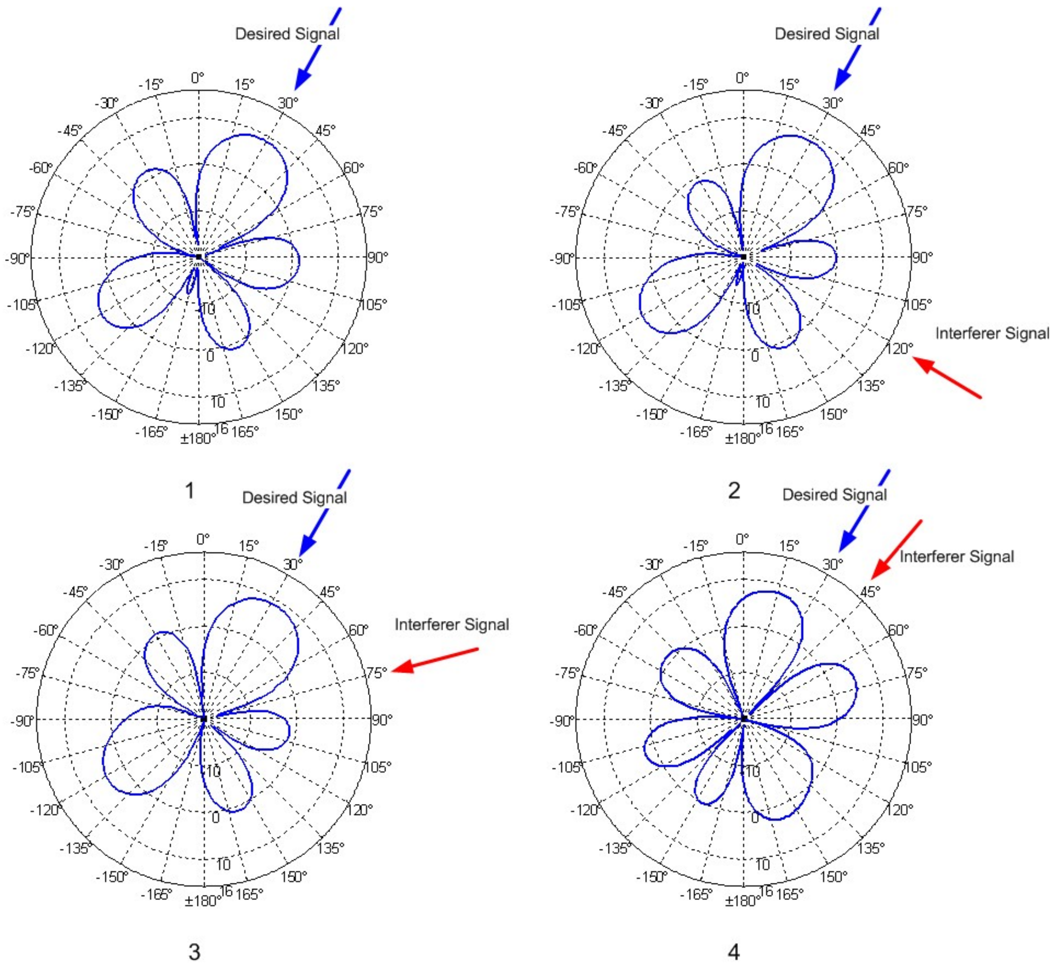

Figure 5.2: Radiation Patterns, 8 element antenna

5.2 Coverage Pattern

Coverage pattern is a suitable mean to highlight the bad influence of large and small scale fading and, in addition, it will be easier to see the benefit of the use of AAA. Note that the problem with such measurements is that it is extremely difficult, if not impossible, to realize them with a practical experience. In this way, the coverage pattern simulation is very useful.

A three-dimensional view has been used where the axes X and Y indicate the location in a plane, and the axis Z, the signal average quality at the output receiver's antenna SNR_{out}. An omni-directional transmitter stands in the middle of the area and receivers are placed in its vicinity. The SNR_{out} is computed at their location. A white plane, $z = 8.5$, corresponding to the BPQK demodulation threshold, has been plotted on the graph. In such way from the top graphic view, all locations from where the receiver can demodulate the transmitted signal are colored and the others are white.

5.2.1 Without small-scale fading

First, let us examine the large-scale fading or, for this simulation, the Free Space Path Loss effect. Figure 5.3 presents the coverage pattern when the receiver uses an omni-directional antenna, an AAA with four and eight elements respectively. The transmitter radiated energy and the noise power stay constant for the three simulations.

Obviously, the utilization of AAA as reception antenna allows to extend dramatically the coverage pattern of the omni-directional antennas, since the coverage surface increases by 300%.

On the other hand, although doubling the number of antenna element from four to eight increases the SNR_{out} from 9 to 12 dB, this does not increase the coverage surface at all. Actually, this is due to the fact that single antennas cannot detect any input signal below 3 decibels (detection threshold).
Typically, the cases on Figure 5.3 considering an AAA with 4 and 8 elements: beyond about 36 meters from the transmitter, the SNR at the AAA input (SNR_{in}) is lower than the detection threshold. In other words, no electric current is induced in the AAA. This is the reason why in this case the SNR_{out} is null (do not confuse with zero dB) with AAA.

5.2.2 With small-scale fading

Secondly, a five rays small-scale fading or Rayleigh Fading has been added. Figure 5.4 shows the fading effect at one time point through the space revealing in this way the locations where the signal cannot be demodulated. But it is important to keep in mind that locations are changing along time.

A simple glance is enough to realize the terrible influence of fading on the received signal quality. Five rays have been used to simulate the fading and their directions of arrival have been randomly chosen in an angle from 0 to 360°.

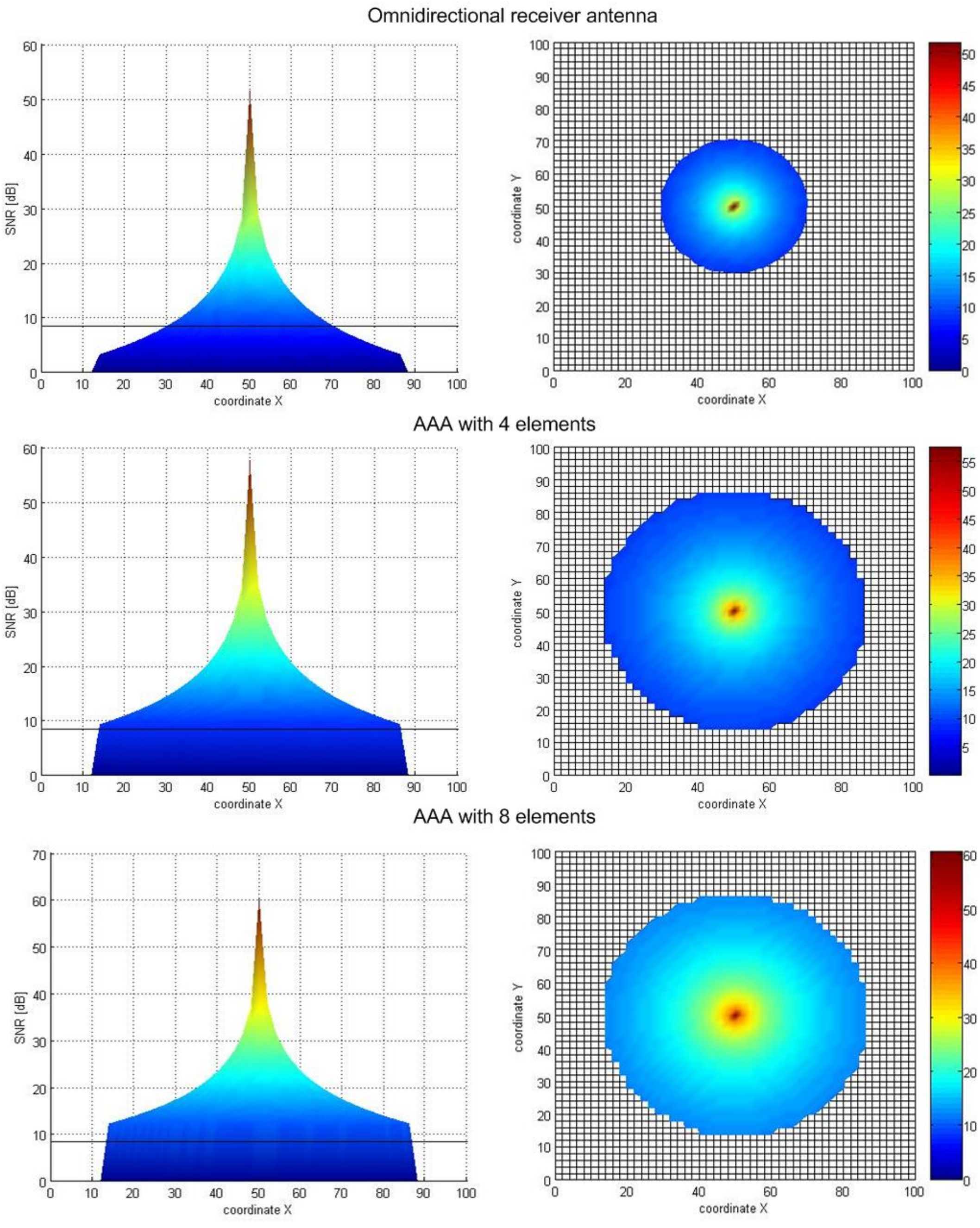

Figure 5.3: Path Loss degradation

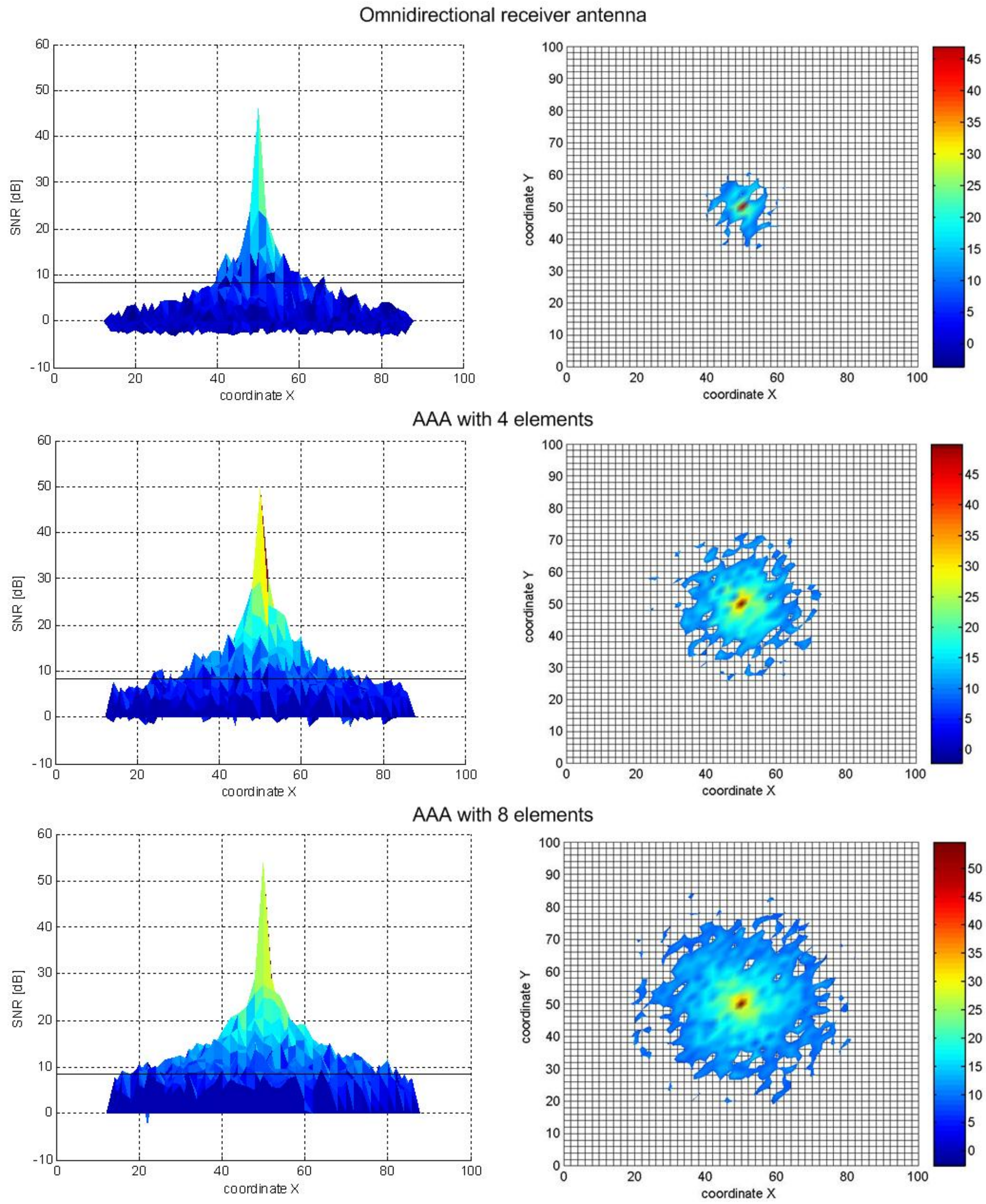

Figure 5.4: Free Space Path Loss & Rayleigh Fading (5 rays) degradation

More scientifically, Figure 5.5 quantifies the benefit resulting from the use of AAA by showing the relative percentage of surface loss due to the Rayleigh fading, according to the number of element antenna in the AAA. Typically, a loss percentage of 100% means the fading removed all locations from which, without Rayleigh fading, terminals could receive the signal, and a probability equals to 0% means the Rayleigh fading does not change anything about the locations where the communication would be available without Rayleigh fading.

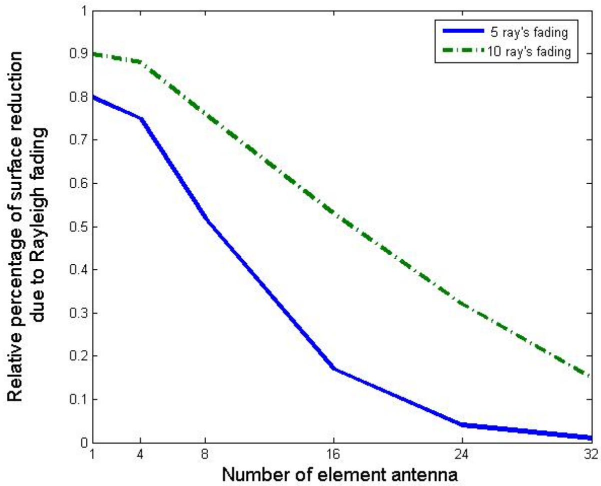

Figure 5.5: Performance of AAA to combat the Rayleigh fading

5.3 Success probability of a RREQ

The previous simulations studied the fading effect only between two terminals, but the main goal of the project is to investigate the consequences of fading from the Network layer perspective when an AAA is used. For this purpose, Figure 5.7 represents the average probability that a RREQ (origin and destination randomly chosen) reaches its destination. This figure includes the results with and without AAA (6-element antenna) and according to several fading degrees (no fading, 5 rays and 10 rays).

It is obvious that the AAA increases the network reliability and the success probability to contact any desired terminal. In the case of 5 rays fading, about 40 terminals equipped with AAA are sufficient to cover the entire simulation area, while more than 120 omni-directional terminals would be needed. Besides, note that the performance of a network equipped with AAA are much less sensitive to fading effect than an identical network equipped with omni-directional antennas.

To get those results, simulations with 500 RREQ trials have been performed. By executing 100 simulations, the probability that RREQ reaches its destination (p) is included, with a certitude coefficient equal to 98 ($\alpha = 98\%$), in following confidence intervals :

Fading	# nodes	Confidence interval with AAA	Confidence interval without AAA
1 ray	20	$0.999 \leq \mu \leq 0.999$	$0.821 \leq \mu \leq 0.829$
5 rays	20	$0.928 \leq \mu \leq 0.939$	$0.138 \leq \mu \leq 0.153$
10 rays	20	$0.537 \leq \mu \leq 0.561$	$0.083 \leq \mu \leq 0.095$

It appears that the intervals are narrow. Therefore, perform 500 trials is sufficient to obtain very accurate results.

5.4 Time and Hop count

Let us just consider the sole RREQs that reach their destination. It is interesting to evaluate the time they need to reach their destination and the hop count of the found routes. Figure 5.6 shows the performance of AODV (RREQ) with and without AAA. For a small number of nodes, the performance of AODV with omni-directional antennas seems better than that with AAA. However, it should be noted that those figures are obtained by counting only successful cases, i.e., the cases in which the request packet could reach to the destination.

Figure 5.7 clarifies this fact.
Firstly, Figure 5.7 shows that the probability that a RREQ reaches its destination is always higher with AAA than with omni-directional antenna. More precisely, the more the fading is important (respectively without fading, 5 and 10 rays fading), larger is the gap between the probability that the RREQ reaches its destination with or without AAA. That demonstrates AAA is less sensitive to fading effect than omni-directional antenna.
Secondly, for a little number of nodes, Figure 5.7 reveals that the omni-directional antenna gives a very low probability that RREQs reach their destination. It means that, even if omni-directional antenna seems better than AAA when the number of nodes is inferior to 30 (5.6), it should be noticed that in this range there are few successful RREQs with omni-directional antenna.

In order to consider the two dimensions of the problem, i.e., the probability that a RREQ reaches its destination and the hop count of the found route. Considering all scenario (either RREQ reaches its destination or not), Figure 5.8 plots the **cumulative distribution function** (CDF) of the time the RREQ takes to reach its destination and the length (hop-count) of the found route. In this way, this simulation focuses on three network configurations: 20, 50 and 100 nodes. With those last figures the performance

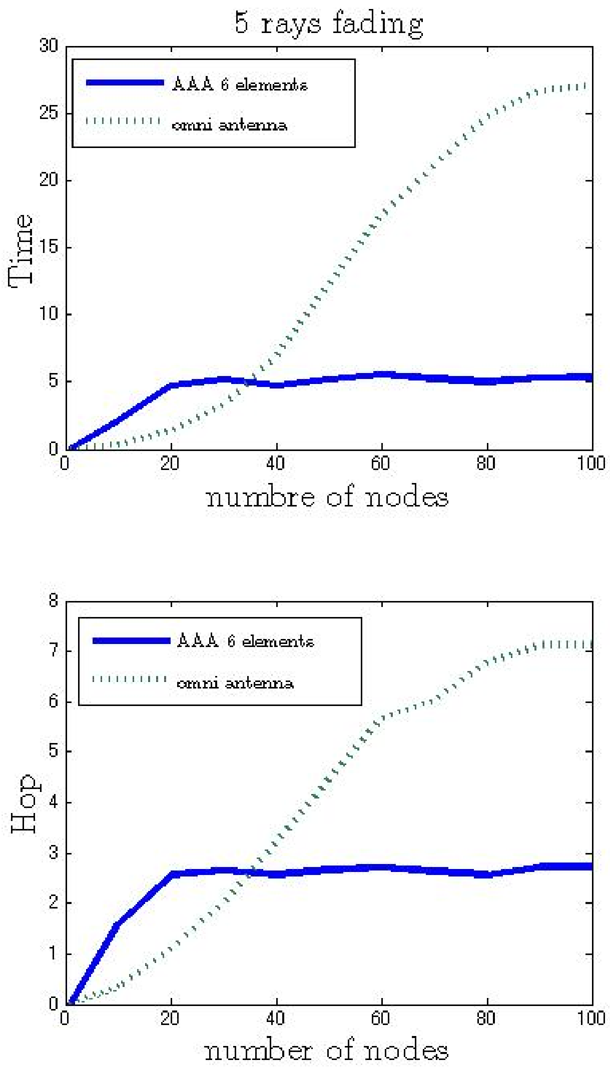

Figure 5.6: Performance overview of Ad hoc network

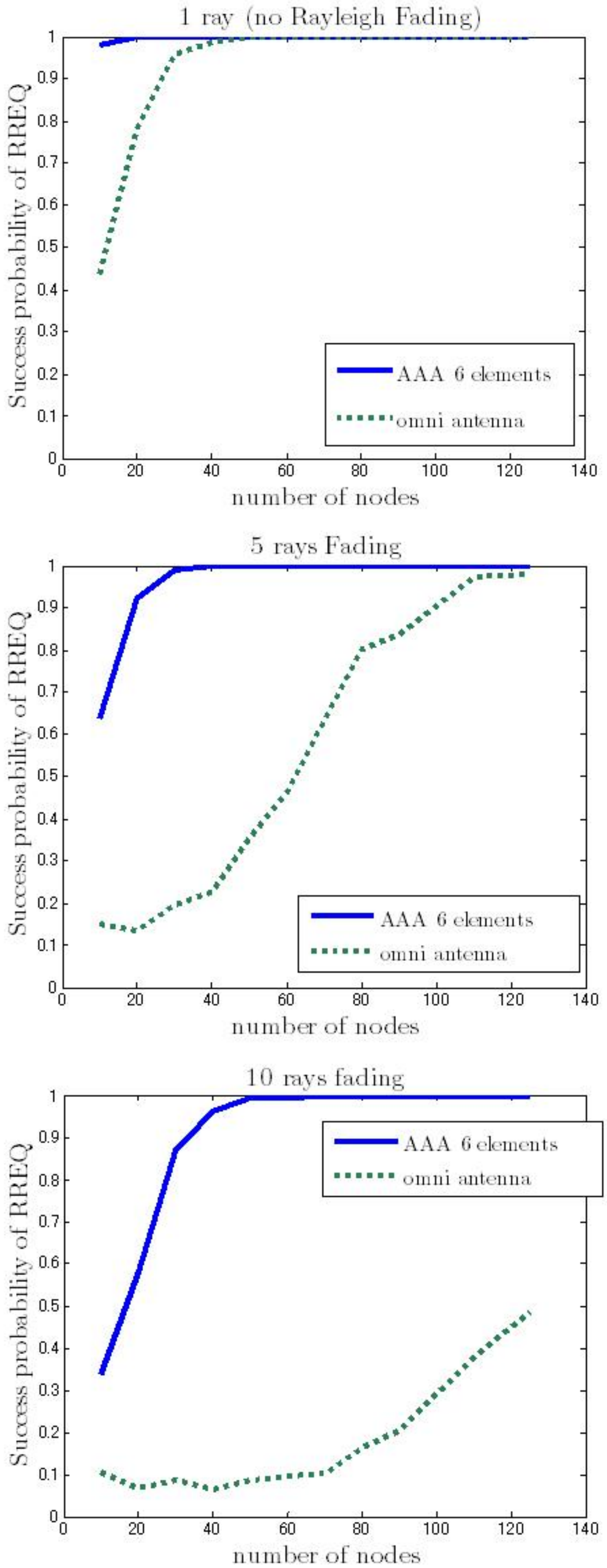

Figure 5.7: Effect of Rayleigh fading from Network layer perspective

of AAA are appreciable. Even if the network is composed of a small number of nodes (e.g., 20 in Figure 5.8), in less than 4 hop, by using AAA about 80% of RREQ reach their destination whereas only about 18% with omni-directional antenna.

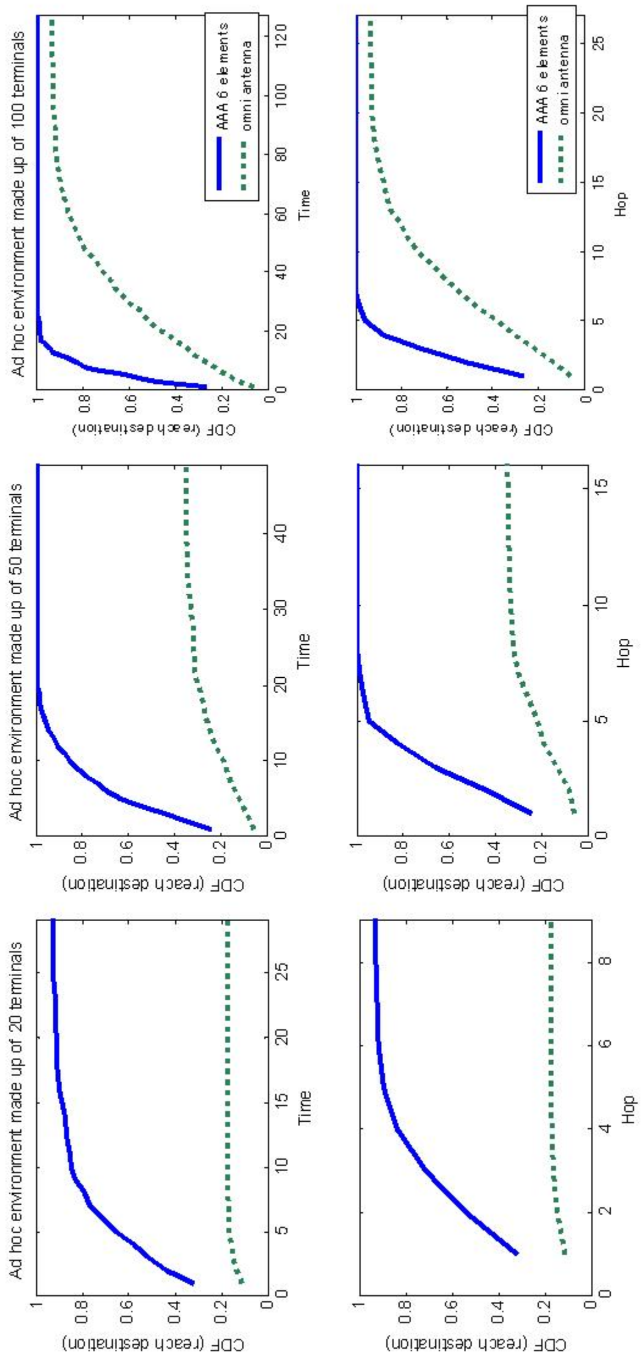

Figure 5.8: Performance of Ad hoc network in term of time and hop count

Chapter 6

Conclusion

This short chapter recalls the main ambitions of the project and reviews its achievements. In addition, it exposes the perspectives for future work.

Often, researches in ad hoc wireless network focus all attention on the higher layers considering unchanged physical layers indices. However the physical layer indices are an important cause of concern from the Electronic Engineering perspective. Typically, the multipath fading phenomenon causes many fluctuations of received signal quality and even sometimes temporary connection loss.

The first goal of the project was to show how fading affects the general performance of an ad hoc network in terms of delay and route hop count.

On the other hand, recent cost reduction of manufacturing for Adaptive Array Antennas might allow us to use this technology more often in wireless systems. Besides, those technologies might provide an excellent mean to overcome fading problems. The demonstration of this fact was the second goal of the project.

Finally, the third goal of the project was to reveal the impact of the use of Adaptive Array Antennas to enhance the performance of ad hoc networks from the network layer perspective.

With those intentions, several computer simulations have been set up and performed. The achievements of this project are listed as follows:

Physical layer A full realistic physical layer model including BPSK modulation-demodulation, Gaussian Noise and fading considerations has been build. The Free Space Path Loss and Rayleigh fading models have been chosen to simulate the large-scale fading and small-scale fading respectively.

AAA The behavior of receiver Adaptive Array Antennas with the Wiener solution and Eigen Value Decomposition has been modelled.

CSMA/CA A simplified version of CSMA/CA considering a discrete time period and an artificial node synchronization mechanism has been implemented.

AODV An AODV multi-hop environment restricted to the packet route request flooding has been studied.

The simulations have produced several meaningful results. Hereunder a list is drawn up with the main findings:

- The fading has a critical impact on the performance of AODV. For instance, the probability to contact another terminal falls drastically when the fading intensity increases.
- In accordance with theoretical results, AAA provides good results to mitigate and overcome the fading problem.
- The use of AAA in ad hoc network environments enhances the performance of network layer in terms of route length and delay. The negative influence of fading at the level of network layer is minimized.

It could be interesting to continue the research to improve the simulation and make it still more conform to the reality. Here is a summary of items for future interesting work:

- Especially the implemented AODV protocol is very simple, the nodes are not likely to fail and cannot move. Moreover, because of the no-necessary bidirectional communication between two terminals, the RREP has not been implemented yet. Considering that MATLAB is not very suitable to implement network layer and routing tables functionalities, it could be judicious to switch to another simulation tool for those components.
- A realistic CSMA/CA model should be developed.

Finally, through this project, one of important key technologies and its effect on the performance improvements of wireless ad hoc networks has been investigated. It is promising that this kind of research results considering not only the network layer but also the physical layer problems pioneers a new vista on wireless networks.

Publications

[**1**] N.François, Y.Kamiya and L.Schumacher, *A consideration on the spatial diversity effect on multi-hop ad hoc networks under Rayleigh fading environments*, General Conference of IEICE*, March 2006, Tokyo, Japan

* IEICE: Institute of Electronics, Information and Communication Engineers, Japan's largest organization of electrical engineers.

Appendix A

Decibel [dB]

The Decibel is the unit used to express relative differences in signal strength. It is expressed as the base 10 logarithm of the ratio of the powers of two signals:

$$dB = 10 \log_{10} \left(\frac{P1}{P2} \right)$$

Signal amplitude can also be expressed in dB. Since power is proportional to the square of a signal's amplitude, dB is expressed as follows:

$$dB = 20 \log_{10} \left(\frac{A1}{A2} \right)$$

Logarithms are useful as measurement units because the signal power tends to vary between several orders of magnitude and because the signal attenuation losses and gains can be expressed in terms of subtraction and addition.
To become used to handle the dB scale, it could be useful to remember the two following equations:

$10 \log_{10}(10) = 10$	$[dB]$
$10 \log_{10}(2) = 3$	$[dB]$

For example, if the power doubles:

$$10 \log 10(power * 2) = 10 \log 10(power) + 10 \log 10(2) = power[dB] + 3$$

When you deal with decibels, only add 3 dB is enough to double power up.

Appendix B

Source Code MatLab

Radiation Pattern

```
%MAIN: RADIATION PATTERN
%++++++++++++++++++++++++
%This simulation is used to plot the radiation pattern of an AAA

clc; clear all; close all;
%Settings
%---------
%Numbre of element antenna
nAntenna = 8;
% preamble for WIener solution
preamble = randint(1,500);
preamble_jammer = randint(1,500);
lgPreamble = length(preamble);
%powers
Prin = 10.^((80)/10);%[Watt]
Prin_jammer = 10.^((80)/10);%[Watt]
Pnin =10.^(1/10);%[Watt]
%Direction of incomming signals
doa = 30;
doa_jammer =45;

%AAA input
%---------
%modulation
Symbols = ModulationBpsk(preamble,Prin,1);
```

```
Symbols_jammer = ModulationBpsk(preamble_jammer,Prin_jammer,1);
%steering vectors
a = SteeringVectorCircle(nAntenna,doa); a_jammer =
SteeringVectorCircle(nAntenna,doa_jammer); X = (a *
Symbols)+(a_jammer * Symbols_jammer)  +
AWGN(nAntenna,
lgPreamble, Pnin);
%Weigner Solution
%-----------------
rxr = X * Symbols' / lgPreamble;
Rxx = (X * X' /lgPreamble);
wOPT = inv(Rxx) * rxr;
wOPT = wOPT/norm(wOPT);
% antenna pattern
[doa,y]=antennapattern(wOPT);
mmpolar(pi*doa/180,y,'RLimit',[-15 16],'Style','compass')
```

Modulation BPSK

```
function [ symbol ] = ModulationBpsk( data, power, nbr_ray)
%  Modulation  BPSK
%  Input: data[1,m]= Data's to modulate
%         power[1,1] = power of signal emission [w]
%         nbr_ray [1,1]= number of rays
%  Output: symbols [nbr_ray, m] correspond to the modulation BPSK
%          For all 1<=j<=m: (|sum{i=1->m}(symbols(i,j))|.^2)=power
%          and
%          For all 1<=i,j<=nbr_ray: symbols(i,:)=symbols(j,:)
%          In other words,
%          the power resulting from superposition of all rays equals to
%          'power' and each ray has the same power.
[n m] = size(data);
symbol = zeros(1,m)+1;
indice1 = find(data==0);
symbol(indice1) = -1;
symbol =  ones(1,nbr_ray)'*(symbol*(sqrt(power)/nbr_ray));%signal amplitude
return
```

Steering Vector

```
function [ a ] = SteeringVectorCircle(nAntenna,DOAdeg)
%This function SteeringVector creates a Steering Vector corresponding to
%the phase differences among the element antennas
%We suppose that the transmitting is sufficiently far
%then DOA is same for each antennas
%   INPUT: nAntenna[1,1] = number of antenna in the array
%          DOA( = direction of arrival signal in radian
%   OUTPUT: a(nAntenna,1) = steering vector for nAntenna which are separate
%       by a distane of "dist" meters and for a transmitter located at "DOA"
%       degrees

lambda = 0.15; %wavelength of wifi signal
dist = lambda/2; %distance between two consecutives antennas
r = dist/(2*sin(pi/nAntenna));%radius of AAA circle
k = 1:nAntenna;
a = exp(
j*(2*pi/lambda)*r *sin(90) * cos((DOAdeg*pi/180)-(2*(pi/nAntenna)*(k-1)))
).';

return
```

White Gaussian Noise

```
function [ noise ] = AWGN(nAntennas,nBit, power )
%    The AWGN function produces a White Gaussian Noise on the channel
%   Input: nAntennas[1,1] = number of antennas that recieve the signal
%          nBit[1,1] = number of data transmited
%          power[1,1] = power of the White Gaussian Noise[W]
%   Output: noise[nAntennas, nBit] = White Gaussian Noise generate for each
%       antennas and data's with the power "power"

%Generation of the noise
%-----------------------
noise = (randn(nAntennas,nBit)+j*randn(nAntennas,nBit))*(sqrt(power)/2);

return
```

Antenna Pattern

```
function[doa,y] = antennapattern(w)
% The function antennapattern compute the amplitude of a signal incomming
% in a AAA composed of 'numel(w)' elements antennas separate from a distance
% wavelength/2
%
%   INPUT: w[n,1] where n is the number of element antennas
%          For all 1<=i<=n: w(i,1) = weigth associate to the antenna i
%          INTERVAL [1,1] = distance between two consecutive antennas
%   OUTPUT: (doa,y) y is the amplitue of incomming signal  corresponding to
%          the direction of arrival 'doa'
[ELEMENT, x] = size(w);
counter= 1;
for DOAtest= 0:360
    y(:,counter)= 20 * log10(abs(w' * SteeringVectorCircle(ELEMENT,DOAtest)));
    counter= counter + 1;
end
doa = -0:360;
return
```

Coverage Pattern

```
%MAIN COVERAGE PATTERN
%++++++++++++++++++++
%This function provides the coverage pattern of an omnidirectionnal
%antenna when the receiver is equipped or no with an AAA.

close all;hold all;clear all;
%Settings
%--------
dimentions = 100;
number_of_coordonate =50 ;
%wavelength for wifi wave
l = 0.15;
% range of antenna's sonstructor specification
ANT_RANGE=20;
%number of elements antennas
nbr_antenna =8;
nbr_ray =10;
```

```
SNRr_limit_modulation = 8.5;%[dB]
SNRr_limit_detection =3;%[dB]
step = (dimentions/number_of_coordonate);
%map Generation (simulate receivers nodes)
%---------------
t = 0:number_of_coordonate;
x =t*step;
y = t*step;
NODE(1,:) = x;
NODE(2,:) = y;
% Position of transmitter
%-------------------------
Tx = [dimentions/2+0.1,dimentions/2+0.1]
%Physical layer configuration
%----------------------------
Pn = 1; %[dB]
%fix the power of transmitters
Pst = MinimalTxPower(SNRr_limit_modulation,Pn,ANT_RANGE);
%Compute the DISTANCE between Tx and other nodes
%-----------------------------------------------
DIST = DistanceFromTx(Tx,NODE);
%Compute the angle between Tx and other nodes
%--------------------------------------------
ANGLE = Angle(NODE, DIST, Tx);
%Compute the SNR with path loss
%------------------------------
SNRrin=SNRr(Pn,Pst,DIST);
%Compute the SNRout with fading
%------------------------------
SNRrout
=SNRAAAWienerFading(SNRrin,Pn,
SNRr_limit_detection,ANGLE,nbr_antenna,nbr_ray);
%Plot the surface
%-----------------
surfc(x,y,SNRrout,'FaceColor','interp'),
shading interp
surf(x,y,SNRr_limit_modulation*ones(length(SNRrin),
length(SNRrin)),'FaceColor','white');
axis([0 100 0 100 -10 60])
xlabel('coordinate X');
ylabel('coordinate Y');
zlabel('SNR [dB]');
grid on
```

Radiation power of the transmitter

```
function [ Pst ] = MinimalTxPower(SNRr_limit_modulation, Pn, antenna_range)
% MinimalTxPower computes the radiation power to have a SNR equal
% to "SNRr_limit_modulation" in a distance from the transmitter equal to
% "antenna_range".
% Asssume we are a free path loss environement and use Wifi technology.
%   INPUT: SNRr_limit_modulation[dB] [n,m]= minimum requirement to demodulate
%        the signal
%          Pn[dB] [1,1]= Power of noise
%          antenna_range[1,1] = distance from transmitter
%   OUTPUT: Pst[dB] [n,m]= power of the transmitter to have a SNR equal
%        to "SNRr_limit_modulation" in a distance from the transmitter
%        equal to "antenna range".

%Variables declaration
%---------------------
l = 0.15; %wavelength for wifi equipements
%SENDING POWER to have the SNR_limit_modulation in the distance ANT_RANGE
Psr =SNRr_limit_modulation + Pn;
Lp = 20*log10(4*pi*antenna_range/l);%[dB]
Pst = Lp + Psr;%[dB]
return
```

Distance between Tx and other nodes

```
function [ DIST ] = DistanceFromTx(Tx,NODE )
% The function DistanceFromTx computes the distance between
% the node Tx and all other nodes in the network.
%   INPUT: Tx[1,2]
%       (Tx(1),Tx(2)) = position of the transmitter node
%          node[5,nbr] where nbr+1 is the number of node
%       for all 1<=i<=nbr:
%       node(1,i) = X coordinate of node i
%       node(2,i) = Y coordinate of node i
%       node(3,i) = reqID that the node i has already received
%       node(4,i) = transmitter of reqID above
%       node(5,i) = number of times that the node i is delayed
%                   consecutively
%   OUTPUT: dist [nbr,nbr]  [meter] for all 1<=i,j<=nbr:
%       dist(i,j) = distance between node i and node j
```

```

%Distance between Tx and other nodes
%-----------------------------------
TxComplex = Tx(1)+ j * Tx(2);
[l,c]=size(NODE);
x = ones(c,1)*NODE(1,:);
y = x.';
complex_expression_of_node_positions = x+i*y;
DIST = abs(complex_expression_of_node_positions - TxComplex);
return
```

Angle between Tx and other nodes

```
function [ ANGLE ] = Angle(NODE, DIST, Tx);
%This function returns the reception angle of signal transmitted from Tx to
%Rx [deg]
[n m] = size(NODE);
Rx =ones(m,1)*NODE(1,:);
ANGLE = asin(abs(Tx(1)-Rx)./DIST);
ANGLE = 180*ANGLE/pi;
return
```

SNR input at the Receivers

```
function [ SNR ] = SNRr(Pn,Pst,DIST)
%This function SNRr computes the maximum SNR at the antennas' receiver input
%between each node of a wifi Network in a free space
%   INPUT: Pn[1,1][dB] = the noise power
%        Pst[1,1][dB] = the tranmitter power radiation
%        DIST [n,n][meter] where n is the number of nodes in the network
%        For all 1<=i,j<=n: DIST(i,j) = distance between node i and node j
%   OUTPUT: SNR [n,n][meter] where n is the number of nodes in the network
%        For all 1<=i,j<=n: SNR(i,j) = SNR at the 'j'node input antenna
%        when the node 'i' send a signal with the power 'Pst' and assume
%        the channel is free space and a white gaussian noise 'Pn'.
%
%wavelength of wifi signal
l = 0.15;
%path loss computation
Lp = 20 * log10(4*pi*DIST/l); %[dB]
```

```
%power recieved
Psr = Pst - Lp; %[dB]
%Matrice of SNRr
SNR = Psr-Pn ;
return
return
```

SNR output at the Receivers

```
function [ SNRout ] =
SNRAAAWienerFading (SNRin,Pnin,limit_detection,ANGLE,nAntenna,nbr_ray)

% SNRAAAWienerFading
% Computes the AAA SNR output from the AAA SNR input
%  INPUT: SNRin [l,c] is the AAA SNR input
%         Pnin [1,1] is the power of the amplifiers noise [dB]
%         limit_detection is the detection SNR treshold
%         ANGLE [l,c] is the angle between node l and c
%         nAntenna [1,1] is the number of element antennas
%           composing the AAA
%         nbr_ray [1,1] represents the intensity of Rayleigh fading
% OUTPUT: SNRout [l,c] is the AAA SNR output


%Settings
spreading_angle = 360;
preamble = randint(1,500);
lgPreamble = length(preamble);

%powers
Prin = 10.^((SNRin + Pnin)/10);%[Watt]
Pnin =10.^(Pnin/10);%[Watt]
[n,m] = size(SNRin);
SNRout = zeros(n,m);
for(l=1:n)
    for(c =1:m)
        if(SNRin(l,c)>=limit_detection)% else no sense to compute the SNRout

            %Random fading generation
            %------------------------
            %Creation of multi signals
```

```
            symbols_ray = ModulationBpsk(preamble,Prin(l,c),nbr_ray);
            %add Phase Shift
            phase_shifting = exp(j*2*pi*rand(1,nbr_ray))'*ones(1,lgPreamble);
            symbols_ray = symbols_ray .* phase_shifting;
            %Selection of DOA for each rays
            theta = ANGLE(l,c);
            inf_mark = theta-(spreading_angle/2);
            sup_mark = theta+(spreading_angle/2);
            DOA_ray =  inf_mark + (sup_mark-inf_mark)* rand(1,nbr_ray);

            % Input of AAA with fading
            %-------------------------
            X = zeros(nAntenna,lgPreamble);
            for(t=1:nbr_ray)
                a(:,t) = SteeringVectorCircle(nAntenna,DOA_ray(t));
            end
            X = (a * symbols_ray)+ AWGN(nAntenna, lgPreamble, Pnin);

            %Wiener Solution
            %----------------
            rxr = X * ModulationBpsk(preamble,Prin(l,c),1)' / lgPreamble;
            Rxx = (X * X' /lgPreamble);
            wOPT = inv(Rxx) * rxr;
            wOPT = wOPT/norm(wOPT);

%           %EigenVectore Solution double
%           %----------------------------
%           [V,D]= eig(X*X');
%           %chose the vector associedto the hiest eigen value
%           [value, indiceMax]= max(max(D));
%           wOPT = V(:,indiceMax);
%           wOPT = wOPT/norm(wOPT);

            %output of AAA
            %--------------
            Y = wOPT' * X;

            %Power signal out [W]
            %----------------
            Psout = sum(abs(Y).^2)/numel(Y);

            %Power noise out [W]
            %---------------
```

```
            Pnout = Pnin * abs(wOPT' * wOPT);

            %SNRout [dB]
            %------
            SNRout(l,c) = 10*log10(Psout / Pnout);
        end
    end
end
return
```

Success probability of a RREQ

```
%MAIN PROBABILITY SUCCESS

clc; close all; clear all;
%Simulation Settings
%-------------------
%number of elements antennas
nbr_elements = 6;
nbrEstim = 1000;
%number of fading ray
nbr_ray = 1;
%number of node on the network
nbrNodeMax = 20;

%Fixed Settings
%--------------
%wavelength for wifi wave
l = 0.15;
% range of antenna's sonstructor specification
ANT_RANGE=30;
%size of the simulation surface
sizeX = 100;
sizeY = 100;
%minimal requirement to demodulate the signal
SNRr_limit_modulation = 8.5;%[dB]
%minimal requirement to detect the signal
SNRr_limit_detection = 3;%[dB]
%power of noise
Pn = 1; %[dB]
%fix the power of transmitters
```

```
Pst = MinimalTxPower(SNRr_limit_modulation,Pn,ANT_RANGE);

%SIMULATION
%++++++++++
%nodes

step=10;
nbrNode = 10:step:nbrNodeMax;
hopAAAWienerFading = 0;
hopantennaFading = 0;
for(estim=1:nbrEstim)
    fprintf('is computing estimation: %d\n',estim);
    l_nbrNode = numel(nbrNode);
    for(cnt=1:l_nbrNode)
        fprintf('nbr node %d \n',nbrNode(cnt));
        %Compute the DISTANCE and ANGLE between each node of the Network
        %---------------------------------------------------------------
        [NODE,DIST,ANGLE] = mapGenerator(nbrNode(cnt),sizeX,sizeY);
        %Consider the FREE SPACE PATH LOSS
        %-------------------------------
        SNRrin=SNRr_central(Pn,Pst,DIST);
        % Tansmitter Receiver:
        %---------------------
        TxRx = randint(1,2,[1,nbrNode(cnt)]);
        %RREQ send:
        %----------
        RREQ = struct('origIP',TxRx(1),'destIP',TxRx(2));
        % AAA antenna with fading
        [t, h]=sendRREQAAAWienerFading(RREQ,SNRrin, NODE, Pn,
                SNRr_limit_modulation, SNRr_limit_detection,ANGLE,
                nbr_elements,nbr_ray );
        hopAAAWienerFading(estim,cnt) = t;
        % normal antenna with fading
        [t,h]=sendRREQAAAWienerFading(RREQ,SNRrin, NODE, Pn,
                SNRr_limit_modulation, SNRr_limit_detection,ANGLE,
                1,nbr_ray );
        hopantennaFading(estim,cnt) = t;
    end
end
%Plot the probability of success
for(cnt=1:l_nbrNode)
   Proba_success(1,cnt) = numel(find(hopAAAWienerFading(:,cnt)~=-1))/nbrEstim;
   Proba_success(2,cnt) = numel(find(hopantennaFading(:,cnt)~=-1))/nbrEstim;
```

```
end
plot(nbrNode,Proba_success)
```

Ad hoc environment generator

```
function [ node, dist, angle] = mapGenerator( nbr,n,m )
%The function mapGenerator generates the coordinates of each node in the
%ad hoc network
% Input: nbr [1,1]= number of node in the ad hoc network
%         (n,m) ([1,1], [1,1])= dimensions of the room where the network
%         takes place
% Output: node[5,nbr] for all 1<=i<=nbr:
%        node(1,i) = X coordinate of node i
%        node(2,i) = Y coordinate of node i
%        node(3,i) = reqID that the node i has already received
%        node(4,i) = transmitter of reqID above
%        node(5,i) = number of times that the node i is delayed
%                    consecutively
%
%        dist [nbr,nbr]  [meter] for all 1<=i,j<=nbr:
%        dist(i,j) = distance between node i and node j
%        angle [nbr,nbr] [degree]for all 1<=i,j<=nbr:
%        angle(i,j) =  angle between node i and node j

%Node creation
%-------------
node(1,:) = sort(n * rand(1,nbr)); % axe-X
node(2,:) = m * rand(1,nbr); %axe-Y

%Display the nodes
% plot(node(1,:),node(2,:),'w^'),axis([0 n 0 m]);
% for (u = 1:nbr)
%     text(node(1,u),node(2,u), int2str(u));
% end

node(3,:) = 0;%reqID
node(4,:) = 0;%transmitter of reqID
node(5,:) = 0;%number retard

%Distance between nodes
%----------------------
```

```
z = node(1,:) + j * node(2,:);
complex_expression_of_node_positions = ones(nbr,1) * z;
dist = abs(complex_expression_of_node_positions.'
-
complex_expression_of_node_positions);
%Angle between nodes
%--------------------
l_dist = length(dist);
angle = zeros(length(dist));
%Only the sub triangular indices are relevant
sub_DIST_indices = find(tril(dist,-1));
Rx =ones(l_dist,1)*node(1,:);
Tx = ones(l_dist,1)*node(1,:);
a = abs(Tx.'-Rx);
angle(sub_DIST_indices) = asin(a(sub_DIST_indices)./dist(sub_DIST_indices));
angle = 180*angle/pi;
angle = angle + angle.';
return
```

SNR input at the Receivers

```
function [ SNR ] =
SNRr_central(Pn,Pst,DIST)
%This function SNRr_central computes the maximum SNR at the
%antenna's receiver input between a node and many others
%   INPUT: Pn[1,1][dB] = the noise power
%          Pst[1,1][dB] = the tranmitter power radiation
%          DIST [n,n][meter] where (n*n) is the number of nodes in the network
%          For all 1<=i,j<=n: DIST(i,j) = distance between node(i,j) and the
%          transmitter node
%   OUTPUT: SNR [n,n][meter] where n is the number of nodes in the network
%          For all 1<=i,j<=n,i~=j: SNR(i,j) = SNR at the 'j'node input antenna
%          when the node 'i' send a signal with the power 'Pst' and assume
%          the channel is free space and a white gaussian noise 'Pn'.
%
%wavelength
l = 0.15;
SNR = zeros(length(DIST));
%Only the sub triangular indices is relevant
sub_DIST_indices = find(tril(DIST,-1));
%path loss computation
Lp = 20 * log10(4*pi*DIST(sub_DIST_indices)/l); %[dB]
```

```
%power recieved
Psr = Pst - Lp; %[dB]
%SMatrice of SNRr
SNR(sub_DIST_indices) = Psr-Pn ;
SNR = SNR + SNR';%[dB]
return
```

RREQ flooding

```
function [ time, hop ] = sendREQAAAWienerFading(RREQ,SNRrin,NODE,Pn,
            limit_modulation, limit_detection,ANGLE,nbr_antenna,nbr_ray )
%The function sendREQAAAWienerFading simulates the sending of a RREQ in
%an an ad hoc network. It computes the time and the number of hop to reach
%from the transmitter, the destination node of the RREQ.

%Assume the network is synchronized. The datalink protocol is an
% hybrid CSMA - slotted ALOHA MAC protocol

%INPUT: RREQ[struct].origIP = number of transmitter node
%                      .destIP = number of destination node
%         SNR [n,n][meter] where n is the number of nodes in the network
%        For all 1<=i,j<=n: SNR(i,j) = SNR at the 'j'node input antenna
%        when the node 'i' send a signal
%         node[5,n] for all 1<=i<=n:
%        NODE(1,i) = X coordinate of node i
%        NODE(2,i) = Y coordinate of node i
%        NODE(3,i) = reqID that the node i has already received
%        NODE(4,i) = transmitter of reqID above
%        NODE(5,i) = number of times that the node i is delayed
%        consecutively
%        Pn [1,1][dB]= power of noise
%        limit_modulation [1,1][dB]=
%        limit_detection [1,1][dB]=
%         ANGLE [n,n] [degree]for all 1<=i,j<=n:
%        ANGLE(i,j) =  angle between node i and node j
%        nbr_antenna[1,1] = number of element antenna in each AAA
%        nbr_ray[1,1] = number of ray
%   OUTPUT: time [1,1] = time to reach the destination node of RREQ
%           hop [1,1] = number of hop to reach the destination node of RREQ
l_SNRrin =length(SNRrin);
%STEP 0: Initialisation of AODV
```

```
%------------------------------
emission = zeros(7,l_SNRrin);
NODE(3,RREQ.origIP) = NODE(3,RREQ.origIP) +1; %increment Tx s'RREQid
emission(1,RREQ.origIP)=1;
emission(2,RREQ.origIP)=1;
emission(3,RREQ.origIP)=NODE(3,RREQ.origIP);
emission(4,RREQ.origIP)=RREQ.origIP;
emission(5,RREQ.origIP)=0;%wait time =0
emission(6,RREQ.origIP)=0;%hop=0
emission(6,RREQ.origIP)=0;%previous
time=0; % time = time pass befor reach the destination
%trouve = 1 if the RREQ reachs the destination else=0
if(RREQ.destIP==RREQ.origIP)
    trouve=1;
else
    trouve=0;
end
SNRrout = zeros(l_SNRrin);
while(trouve==0 && length(find(emission(1,:)~=0))~=0)
    time = time+1;
    %STEP 1: Physical layer
    %----------------------
    applicants_list_transmition = find(emission(1,:)==1 & emission(2,:)==time);
    %compute the fading and the SNRoutput resulting
    SNRrout(applicants_list_transmition,:) =
SNRAAAWienerFading(SNRrin(applicants_list_transmition,:),Pn,
limit_detection,ANGLE,nbr_antenna,nbr_ray);
    % STEP 2: MAC
    %------------
    %Find node that can transmit in the instant "time"
    %applicants_list_transmition = node that want transmitter now

    %waiting time incrementation(suppose that nobody will can transmitter
    emission(5,applicants_list_transmition)=emission(5,
                                    applicants_list_transmition)+1;
    if(length(applicants_list_transmition)~=0)
        %selection of transmitter(s)
        applicants_list_transmition =
            applicants_list_transmition(randperm(
                                length(applicants_list_transmition)));
        tansmitters=0;
        transmitters(1)=applicants_list_transmition(1);
        l_applicants_list_transmition = numel(applicants_list_transmition);
```

```
        for(t=2:l_applicants_list_transmition)
            %the applicant can transmits only if his propagation range
            %doesn'disturb the others transmitters
            applicant = applicants_list_transmition(t);
            %1: the node must not be in the same radiation area
            too_close_node =
                transmitters(find(SNRrout(transmitters,applicant)
                        >=limit_detection));
            if(length(too_close_node)==0)
                %2: the applicant nodes must not have any common node with
                % transmitters
                [nodes_accessible,I]=ind2sub(size(SNRrout),
                    find(SNRrout(applicant,:)>=limit_detection));
                common_node = find(SNRrout(transmitters,nodes_accessible)
                                            >=limit_detection);
                if(length(common_node)==0)
                    transmitters(length(transmitters)+1)=applicant;
                end
            end
        end
        % generation delay(exponential Back off) and add to node
        maxBorne_list = 2.^(min(ones(1,
            length(applicants_list_transmition))*10,
            emission(5,applicants_list_transmition)))-1;
        delays = 0;
        l_maxBorne_list = numel(maxBorne_list);
        for(t=1:l_maxBorne_list)
            delays(t)  = randint(1,1,[1 maxBorne_list(t)]);
        end
        emission(2,applicants_list_transmition)
                = emission(2,applicants_list_transmition)+delays;
        %STEP 3: AODV sending
        %--------------------
        %MAJ matrix emission
        emission(1,transmitters) = 0; %now transmitters doesn't want
        emission(2,transmitters) = 0; % any more transmit.
        emission(3,transmitters) = RREQ.origIP;%save that he already send
        emission(4,transmitters) = NODE(4,RREQ.origIP);%this RREQ.
        emission(5,transmitters) = 0;%wait time =0
        %STEP 4: TRANSMITION over channel
        %--------------------------------
        receivers=0;
        l_transmitters = numel(transmitters);
```

```
        for(t=1:l_transmitters)
            Tx =transmitters(t);
            [new_receivers, I] = ind2sub( l_SNRrin,
                    find(SNRrout(Tx,:)>=limit_modulation));
%            %plot the RREQ
%            l_new_receivers =numel(new_receivers);
%             for(r=1:l_new_receivers)
%                 Rx = new_receivers(r);
%                 drawnLink(NODE(1,Tx),NODE(2,Tx),NODE(1,Rx),NODE(2,Rx),1);
%             end
            emission(6,new_receivers)=Tx;
            receivers = [receivers ,new_receivers];
        end
    end
    receivers = receivers(find(receivers>0));
    if(length(find(receivers==RREQ.destIP))>0)
        trouve=1;
    end
    %STEP 5:AODV preparing next step
    %-------------------------------
    %selection of node that must forward the message ie: they haven't
    %yet had  the message
    node_forward = receivers(find(
        emission(3,receivers)~=emission(3,transmitters(1)) |
        emission(4,receivers)~=emission(4,transmitters(1))
        ));
    emission(1,node_forward)=1;
    emission(2,node_forward)=time+1;
    emission(3,node_forward)=emission(3,transmitters(1));
    emission(4,node_forward)=emission(4,transmitters(1));
    previousHop=1+emission(7,emission(6,node_forward));
    emission(7,node_forward)=previousHop;
end
if(trouve==0)
    time = -1;
    hop = -1;
else%the destination node had been found
    emission(1,RREQ.destIP)=0;
    hop =  emission(7,RREQ.destIP);
end
return
```

Time and Hop count

```
% MAIN TIME AND HOP COUNT
%This Program simules many sends of RREQ in a AD-HOC network coposed of
%many nodes. It computes the average time and hop count.
%
%It uses thoses layers:
%   NetworkLayer = AODV
%   DataLinkLayer = CSMA
%   PhysicalLayer = AAA
%
%We consider a medium with fading.
%With this simulation you can define the scenarii
%   1. number of element antennas of AAA
%   2. the number of fading rays
%This prgram shows for each scenarii and for a random transmitter and
%receiver:
%   The time that takes a RREQ from transmitter to receiver
%   The number of Hop computed by AODV
%
%Moreover, it reveals the pourcentage of failure for each scenarii
clc;
close all;
clear all;

%Settings
%--------
%wavelength for wifi wave
l = 0.15;
% range of antenna's sonstructor specification
ANT_RANGE=20;
%size of the simulation surface
sizeX = 100;
sizeY = 100;
%number of elements antennas
nbr_elements = [1 3 4 6];
l_nbr_elements = numel(nbr_elements);
%number of fading ray
nbr_ray = 5;
%minimal requirement to demodulate the signal
SNRr_limit_modulation = 8.5;%[dB]
%minimal requirement to detect the signal
```

```
SNRr_limit_detection = 3;%[dB]
%power of noise
Pn = 1; %[dB]
%fix the power of transmitters
Pst = MinimalTxPower(SNRr_limit_modulation,Pn,ANT_RANGE);

%SIMULATION
%++++++++++
nbrEstim = 1;
%nodes
nbrNodeMax = 100;
step=10;
t =1:(nbrNodeMax/step);
nbrNode = [1, t*step];


sumTimeAAAWiener= 0;
sumHopAAAWiener = 0;
sumTimeAAAWienerFading = 0;
sumHopAAAWienerFading = 0;


echecAAAWiener = zeros(1,l_nbr_elements);
echecAAAWienerFading = zeros(1,l_nbr_elements);
for(estim=1:nbrEstim)
    fprintf('is computing estimation: %d\n',estim);
    l_nbrNode = numel(nbrNode);
    for(cnt=1:l_nbrNode)
        fprintf('nbr node %d \n',nbrNode(cnt));
        %Compute the DISTANCE and ANGLE between each node of the Network
        %----------------------------------------------------------------
        [NODE,DIST,ANGLE] = mapGenerator(nbrNode(cnt),sizeX,sizeY);
        %Consider the FREE SPACE PATH LOSS
        %---------------------------------
        SNRrin=SNRr_central(Pn,Pst,DIST);
        % Tansmitter Receiver:
        %---------------------
        TxRx = randint(1,2,[1,nbrNode(cnt)]);
        %RREQ send:
        %----------
        RREQ = struct('origIP',TxRx(1),'destIP',TxRx(2));

        for(el=1:l_nbr_elements)
```

```
            % AAA antenna without fading
            [t, h]=sendRREQAAAWiener(RREQ,SNRrin, NODE, Pn,
SNRr_limit_modulation, SNRr_limit_detection,ANGLE,nbr_elements(el));
            if(t==-1)
                echecAAAWiener(el) = echecAAAWiener(el) +1;
            end
            timeAAAWiener(el,cnt) = t;
            hopAAAWiener(el,cnt) = h;
            % AAA antenna with fading
            [t,h]=sendRREQAAAWienerFading(RREQ,SNRrin, NODE, Pn,
SNRr_limit_modulation, SNRr_limit_detection,ANGLE,nbr_elements(el),nbr_ray );
            if(t==-1)
                echecAAAWienerFading(el) = echecAAAWienerFading(el) +1;
            end
            timeAAAWienerFading(el,cnt) = t;
            hopAAAWienerFading(el,cnt) = h;
        end
    end
    sumTimeAAAWiener = sumTimeAAAWiener + timeAAAWiener;
    sumHopAAAWiener = sumHopAAAWiener + hopAAAWiener;
    sumTimeAAAWienerFading = sumTimeAAAWienerFading + timeAAAWienerFading;
    sumHopAAAWienerFading = sumHopAAAWienerFading + hopAAAWienerFading;
end
% AAA antenna without fading
averageTimeAAAWiener = sumTimeAAAWiener/nbrEstim
averageHopAAAWiener = sumHopAAAWiener/nbrEstim
subplot(2,2,1),plot(nbrNode,averageTimeAAAWiener(1,:),nbrNode,
    averageTimeAAAWiener(2,:),nbrNode,averageTimeAAAWiener(3,:),
    nbrNode,averageTimeAAAWiener(4,:));

subplot(2,2,2),plot(nbrNode,averageHopAAAWiener(1,:),nbrNode,
    averageHopAAAWiener(2,:),nbrNode,averageHopAAAWiener(3,:),
    nbrNode,averageHopAAAWiener(4,:));
title('AAA antenna without fading');
% AAA antenna with fading
averageTimeAAAWienerFading = sumTimeAAAWienerFading/nbrEstim;
averageHopAAAWienerFading = sumHopAAAWienerFading/nbrEstim;
subplot(2,2,3),plot(nbrNode,averageTimeAAAWienerFading(1,:),
    nbrNode,averageTimeAAAWienerFading(2,:),nbrNode,
    averageTimeAAAWienerFading(3,:),nbrNode,
    averageTimeAAAWienerFading(4,:));
subplot(2,2,4),plot(nbrNode,averageHopAAAWienerFading(1,:),
    nbrNode,averageHopAAAWienerFading(2,:),
```

```
    nbrNode,averageHopAAAWienerFading(3,:),nbrNode,
    averageHopAAAWienerFading(4,:));
title('AAA antenna with fading');

%Error pourcentage
nbr_elements
nbr_tot_RREQ = nbrEstim * numel(nbrNode);
echecPourcentageWienerFading = (echecAAAWienerFading/nbr_tot_RREQ)*100
echecPourcentageWiener = (echecAAAWiener/nbr_tot_RREQ)*100

```

Cumulative distribution function

```
%MAIN Histogramme CDF

% This simulation organize the time and hop count in a cummulative
%   distribution function

clc; close all; clear all;
%Simulation Settings
%--------------------
%number of element antenna
nbr_elements = 6;
nbrEstim = 300;
%nodes
nbrNode =20;
%number of fading ray
nbr_ray = 5

%Fixed Settings
%--------------
%wavelength for wifi wave
l = 0.15;
% range of antenna's sonstructor specification
ANT_RANGE=30;
%size of the simulation surface
sizeX = 100;
sizeY = 100;
%minimal requirement to demodulate the signal
SNRr_limit_modulation = 8.5;%[dB]
%minimal requirement to detect the signal
```

```
SNRr_limit_detection = 3;%[dB]
%power of noise
Pn = 1; %[dB]
%fix the power of transmitters
Pst = MinimalTxPower(SNRr_limit_modulation,Pn,ANT_RANGE);

%SIMULATION
%++++++++++

for(estim=1:nbrEstim)
    fprintf('is computing estimation: %d\n',estim);
    %Compute the DISTANCE and ANGLE between each node of the Network
    %------------------------------------------------------------
    [NODE,DIST,ANGLE] = mapGenerator(nbrNode,sizeX,sizeY);
    %Consider the FREE SPACE PATH LOSS
    %---------------------------------
    SNRrin=SNRr_central(Pn,Pst,DIST);
    % Tansmitter Receiver:
    %---------------------
    TxRx = randint(1,2,[1,nbrNode]);
    %RREQ send:
    %----------
    RREQ = struct('origIP',TxRx(1),'destIP',TxRx(2));
    % AAA antenna with fading
    [t, h]=sendRREQAAAWienerFading(RREQ,SNRrin,
NODE, Pn, SNRr_limit_modulation, SNRr_limit_detection,ANGLE,
nbr_elements,nbr_ray);
    Time(estim,1) = t;
    Hop(estim,1) = h;
    % antenna normal with fading
    [t, h]=sendRREQAAAWienerFading(RREQ,SNRrin,
NODE, Pn, SNRr_limit_modulation, SNRr_limit_detection,ANGLE,
1,nbr_ray);
    Time(estim,2) = t;
    Hop(estim,2) = h;
end
Echec_rate_AAA = numel(find(Time(:,1)==-1))/nbrEstim
Echec_rate_antenna = numel(find(Time(:,2)==-1))/nbrEstim


max_time = max(max(Time));
max_hop = max(max(Hop));
Time(find(Time==-1))=max(max(Time))+10;
```

```
Hop(find(Hop==-1))=max_hop+10;

%TIME
[n,xTime] = hist(Time,[1:1:max(max(Time))+2]);
n(:,1) = n(:,1)/sum(n(:,1));
n(:,2) = n(:,2)/sum(n(:,2));
n = cumsum(n);
subplot(2,1,1);plot(xTime,n);

%HOP
clear n;
[n,xHop] = hist(Hop,[1:1:max(max(Hop))+2]);
n(:,1) = n(:,1)/sum(n(:,1));
n(:,2) = n(:,2)/sum(n(:,2));
n = cumsum(n);
subplot(2,1,2);plot(xHop,n);
```

Appendix C

Publication

レイリーフェージング環境下のマルチホップ無線アドホックネットワークにおける空間ダイバーシティ効果に関する一検討

A consideration on the spatial diversity effect on multi-hop ad hoc networks under Rayleigh fading environments

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1 Introduction

Although applications of diversity antennas to wireless ad hoc networks have been paid attention, the performance of multi-hop networks under Rayleigh fading has not been very well examined. In this short paper, the performance improvement brought by the diversity antenna will be clarified through computer simulations.

2 Formulations

The received signal consisting of M element waves received by N antennas are expressed as a vector of size $(N \times 1)$ as follows:

$$\boldsymbol{x}(t) = \sum_{m=1}^{M} \frac{\sqrt{P_S}}{M} \boldsymbol{a}(\theta_m) s(t) e^{j\phi_m} + \sqrt{\frac{P_N}{2}} \boldsymbol{\eta}(t) \quad (1)$$

where $\boldsymbol{a}(\theta_m) \in \mathcal{C}^{N\times 1}$ is the steering vector as a function of the direction of arrival (DOA) $\theta_m$while ϕ_m is the initial phase. The subscript $\cdot_m$ denotes the m-th element wave. The noise vector with the unit power is denoted by $\boldsymbol{\eta}(t) \in \mathcal{C}^{N\times 1}$. Then, the signal-to-noise power ratio (SNR) of the received signal Γ_{in} is defined as P_S/P_N.

Then, the correlation matrix $\boldsymbol{R}_{xx} \in \mathcal{C}^{N\times N} = \mathcal{E}[\boldsymbol{x}\boldsymbol{x}^{\mathcal{H}}]$ is decomposed by the eigenvalue decomposition (EVD) to obtain the weight vector $\boldsymbol{w} \in \mathcal{C}^{N\times 1}$ by the eigenvector corresponding to the maximum eigenvalue. Here, $\mathcal{E}[\cdot]$ denotes the emsemble average. Note that $\|\boldsymbol{w}\| = 1$. Then, the antenna output is obtained by $y(t) = \boldsymbol{w}^H \boldsymbol{x}(t)$ with the antenna output SNR Γ_{out} as:

$$\Gamma_{out} = \frac{|\sum_{m=1}^{M} \frac{\sqrt{P_S}}{M} \boldsymbol{w}^H \boldsymbol{a}(\theta_m)|^2}{P_N} \quad (2)$$

3 Computer simulations

Table 1 lists simulation conditions. We assume an on-demand type wireless ad hoc network with AODV [1] for the route finding. Also, it is assumed that the media access control employs CSMA/CA. All nodes are under Rayleigh fading consisting of 10 element waves. Then, we compare the performance in terms of the number of the necessary hops till the arrival of Route REQest (RREQ) packets to the destination with and without the antenna diversity. In this simulation, it is considered that the channel is unavailable if $\Gamma_{out} < 8.5$[dB]. Figure 1 shows the success rate of RREQ versus the number of nodes. It is seen that the antenna diversity contributes to the improvement of the RREQ success rate due to the compensation of fading. Figure 2 shows Cumulative probability Distribution Function (CDF) for the number of hop only when RREQs are successful. It is clearly found that the antenna diversity reduces the number of hops also drastically.

表 1 Simulation conditions

Antenna	6-element circular
Path loss	Free space (square-law)
Receiving SNR Γ_{in}	10[dB] @ 10m
Num. of element waves M	10
DOA θ_m	Uniformly random within [0,360][deg]
Phase ϕ_m	Uniformly random within $[0, 2\pi]$[rad]

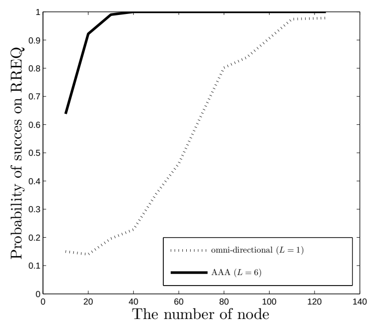

図 1 The number of nodes versus RREQ success rate

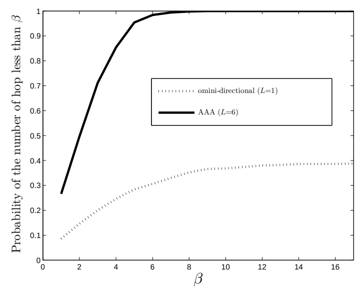

図 2 CDF of the number of hop

4 Concluding remarks

In this short paper, we clarify the effect of the antenna diversity under Rayleigh fading to the performance of the wireless ad hoc networks with AODV in terms of the number of hops. More realistic scenario will be reflected in the simulations as a further consideration.

参考文献

[1] C-K.Toh, "Ad Hoc Mobile Wireless Networks: Protocols and Systems," Prentice Hall, 2001.

Bibliography

[Aut] Several Unknown Authors. Signal, Fading, Antenna, Mobile ad-hoc network. *Wikipedia, the free encyclopedia, http://en.wikipedia.org/*. Date consulted: May, 2006.

[Aut04] Various Author. *Adaptive Antenna Arrays (Trends and Applications)*. Springer, 2004.

[Bel98] Maurice Bellanger. *Traitement numérique du signal (Théorie et pratique)*. 7ème edition, december 1998.

[BS04] Giordano S Stojmenovic I. Basagni S., Conti M. *Mobile Ad Hoc Networking*. IEEE Press, 2004.

[Con03] IEC (International Engineering Consortium). Smart Antenna Systems. Tutorial Network Working Group, The Internet Society, 2003.

[C.P03] S.Das C.Perkins, E.Belding-Royer. RFC 3561 - Ad hoc On-Demand Distance Vector (AODV) Routing. *Network Working Group, The Internet Society*, 2003.

[Fee99] Laura Marie Feeney. A Taxonomy for Routing Protocols in Mobile Ad Hoc Networs. Technical report, Swedish Institute of Computer Science, 1999.

[J.E03] J.E.Hudson. *Adaptive array principles*. Peter Peregrinus Ltd., London, 2003.

[Joh05] Don Johnson. Comparison of Analog and Digital Communication. *http://cnx.rice.edu/content/m0074/latest/*, April 2005.

[Lev03] O. Levin. RFC 3508: H.323 Uniform Resource Locator (URL) Scheme Registration. *Network Working Group, The Internet Society*, April 2003.

[Noi03] Monique Noirhomme. Probabilités et Statistiques. Technical report, Faculté des Sciences économiques sociales et de gestion, Université de Namur (FUNDP), 2002-2003.

[OHHL05] Tarek N. Saadawi Osama H. Hussein and Myung Jong Lee. Probability routing Algorithm for Mobile Ad Hoc Networks' Resources Management. *IEEE Journal on Selected Areas In Communications*, 23:2248, December 2005.

[Ros02] J. Rosenberg. RFC 3261: SIP (Session Initiation Protocol). *Network Working Group*, June 2002.

[S.C99] J.Macker S.Corson. RFC 2501 Mobile Ad hoc Networking (MANET): Routing Protocol Performance Issues and Evaluation Considerations. *Network Working Group, The Internet Society*, 1999.

[Skl97] Bernard Sklar. Rayleigh Fading Channels in Mobile Digital Communication Systems Part I: Characterization. *IEEE Communication Magazine*, July 1997.

[Skl01] Bernard Sklar. *Digital Communication: Fundamentals and Applications (2nd Edition).* PHPTR, 2001.

[Thi03] JP. Thiran. Algèbre Supérieure I, II. Technical report, Faculté des Sciences économiques, sociales et de gestion, 2001-2002-2003.

[VGLL05] Ge Y. Villasenor-Gonzalez L. and Lamont L. HOLSR: A Hierarchical Proactive Routing Mechanism for Mobile Ad Hoc Networks. *IEEE Communications Magazine*, pages 118–125, July 2005.

[Wei99] Eric W. Weisstein. Monte Carlo Method. *http://mathworld.wolfram.com/MonteCarloMethod.html*, 1999.

[Y.K05] Y.Kamiya. Telecommunication I/II. Technical report, Tokyo University of Agriculture and Technology, Departement of Electrical and Electronics Engineering, Tokyo, 2005.